Fisheries and Oceans Canada | Pêches et Océans Canada
Science | Sciences

C S A S | **S C C S**

Canadian Science Advisory Secretariat | **Secrétariat canadien de consultation scientifique**

Research Document 2010/040 | **Document de recherche 2010/040**

A Geographic Information System (GIS) Simulation Model for Estimating Commercial Sponge By-catch and Evaluating the Impact of Management Decisions

Un modèle de simulation à partir d'un système d'information géographique (SIG) pour évaluer les prises accidentelles d'éponges commerciales et évaluer l'incidence des décisions en matière de gestion

E. Kenchington[1], A. Cogswell[1], C. Lirette[1] and J. Rice[2]

Fisheries and Oceans Canada

[1]Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia
Canada B2Y 4A2

[2]National Capital Region, Science Branch
200 Kent Street
Ottawa, Ontario
Canada K1A 0E6

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

La présente série documente les fondements scientifiques des évaluations des ressources et des écosystèmes aquatiques du Canada. Elle traite des problèmes courants selon les échéanciers dictés. Les documents qu'elle contient ne doivent pas être considérés comme des énoncés définitifs sur les sujets traités, mais plutôt comme des rapports d'étape sur les études en cours.

Research documents are produced in the official language in which they are provided to the Secretariat.

Les documents de recherche sont publiés dans la langue officielle utilisée dans le manuscrit envoyé au Secrétariat.

This document is available on the Internet at:

Ce document est disponible sur l'Internet à:

http://www.dfo-mpo.gc.ca/csas/

ISSN 1499-3848 (Printed / Imprimé)
ISSN 1919-5044 (Online / En ligne)
© Her Majesty the Queen in Right of Canada, 2010
© Sa Majesté la Reine du Chef du Canada, 2010

Canada

TABLE OF CONTENTS

ABSTRACT v

RÉSUMÉ vi

INTRODUCTION 1

METHODS 1

Description of Model Input Data Layers 1
Description of the Model 2
Evaluation of Model Outcomes 7

RESULTS 7

Simulated Sponge By-catch Less than 800 kg/tow 9
Simulated Sponge By-catch Greater than 800 kg/tow 10

DISCUSSION 11

Improving the Information Content of the Simulation 12

REFERENCES 12

FIGURES 14

Correct citation for this publication:

Kenchington, E., Cogswell, A., Lirette, E., and Rice, J. 2010. A Geographic Information System (GIS) Simulation Model for Estimating Commercial Sponge By-catch and Evaluating the Impact of Management Decisions. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/040. vi + 40 p.

ABSTRACT

A Geographic Information System (GIS) simulation model was developed to assess management decisions pertaining to commercial sponge by-catch by the Greenland halibut fishery in the Northwest Atlantic Fisheries Organization (NAFO) Regulatory Area (NRA). Sponge biomass by-catch from research vessel stratified random surveys was interpolated using an inverse distance weighted (IDW) algorithm to produce a smoothed surface. Data on fishing effort were interpolated using a kriging procedure and were used to weight both start positions of simulated trawls, as well as trawl direction. These weighted positions (Model B) were contrasted with randomly placed start positions with random trawl direction (Model A). In order to evaluate the effect of area closures put in place by NAFO on the simulated sponge by-catch, Models A and B were each run iteratively under two scenarios: 1) simulated trawl lines within the fishing footprint, and 2) simulated trawl lines within the fishing footprint and outside of the closure areas. For each of the four outcomes, 1500 simulated sponge by-catch weights were used to evaluate the effect of spatial closures and an 800 kg encounter threshold for commercial catches. The model suggests that the current area closures to protect coral and sponge grounds will have reduced sponge by-catch by 28% if fishing effort was distributed as it had been for the previous 20 years. It also estimated that 8.5% of the by-catch records were over 800 kg, with most of these found adjacent to the Sackville Spur sponge closure or the Flemish Pass area closure, and along the canyon heads of the Grand Banks. The model indicates that reducing the encounter threshold from 800 kg to 100 kg/37 km tow would only affect a further 8% of the simulated by-catch records and protect sponges at the canyon heads of the Grand Banks and in the slope waters of Flemish Pass.

RÉSUMÉ

On a mis au point un modèle de simulation à partir d'un modèle de simulation à partir d'un système d'information géographique (SIG) afin d'évaluer les décisions de gestion en ce qui a trait aux prises accidentelles d'éponges dans la pêche commerciale de flétan du Groenland dans la zone réglementée par l'Organisation des pêches de l'Atlantique Nord-Ouest (OPANO). La biomasse des prises accidentelles des éponges provenant des relevés aléatoires stratifiés faits par des navires de recherche a été interpolée au moyen d'un algorithme de pondération en fonction de l'inverse de la distance (IDW) de façon à produire une surface lissée. Les données relatives à l'effort de pêche ont été interpolées au moyen d'une procédure de krigeage et on les a utilisées pour pondérer à la fois les positions de départ de chaluts simulés ainsi que leur direction. Ces positions pondérées (modèle B) ont été mises en contraste avec les positions de départ choisies de façon aléatoire avec la direction aléatoire des traits de chalut (modèle A). Pour évaluer l'incidence des pêches que l'OPANO a interdites dans certaines zones sur les prises accidentelles simulées, les modèles A et B ont été exécutés de façon itérative dans le cadre de deux scénarios : 1) des aires balayés par les chaluts simulées au sein de l'empreinte de la pêche, et 2) des lignes de fond simulées au sein de l'empreinte de la pêche et à l'extérieur des zones de pêche interdite. Pour chacun des quatre résultats, on a utilisé 1 500 facteurs de pondération de captures d'éponges afin d'évaluer l'incidence de fermetures de type spatial et un seuil de rencontre de 800 kg dans le cas des prises commerciales. Le modèle laisse entendre que les pêches actuellement interdites dans le but de protéger les zones où se trouvent les éponges auront permis de réduire les prises accidentelles d'éponges de 28 % si l'effort de pêche avait été répartie de la même façon que dans les 20 dernières années. Il estimait également que 8,5 % des captures accessoires dépassaient 800 kg, la plupart provenant des zones adjacentes au secteur de la pêche interdite d'éponges de l'éperon de Sackville ou du passage Flamand, ainsi que le long des têtes de canyon des Grands Bancs de Terre-Neuve. Le modèle indique que le fait de faire passer le seuil de 800 kg à 100 kg/37 km par trait aurait une incidence de seulement 8 % de plus des captures accessoires simulées et protégerait les éponges aux têtes de canyon des Grands Bancs de Terre-Neuve et dans les eaux du talus continental du passage Flamand.

INTRODUCTION

Simulation models can be used to evaluate outcomes of fisheries management decisions. In the present application we detail how information on sponge by-catch from research vessel surveys can be used in combination with data on fishing effort to estimate commercial trawl sponge by-catch. This is an important application because data on commercial trawl catches have a number of deficiencies that render them questionable for quantitative evaluation, e.g., 1) observers on the vessels have differing abilities to recognize invertebrate or other non-commercial by-catch, 2) time constraints on commercial vessels may not allow for accurate sorting and recording of taxon-specific weights, 3) if only one observer is present on a vessel records may not be made during times off watch, and/or 4) some fisheries have incomplete observer coverage. Consequently, data from fisheries observer programs can suffer from varying degrees of imprecision and inaccuracy and, in general, can only be used to indicate presence of non-commercial species unless data collection is closely monitored and validated. At the same time, there is a requirement to provide a scientific basis for management actions to manage and ensure sustainability of the impacts of commercial fishing operations on vulnerable marine ecosystems (VMEs) such as those underpinned by benthic structure-forming species such as large sponges.

Here we outline a method based on simulation modelling which will provide estimates of commercial sponge by-catch. This model evolved through the need to address management questions within the Northwest Atlantic Fisheries Organization (NAFO) and so the simulation is applied to the NAFO Regulatory Area (NRA) on Flemish Cap and the southwest Grand Banks using fishing scenarios estimated for the Greenland halibut (turbot) fishery there. There are no Canadian commercial sponge by-catch data for the NRA, although collection of data on sponges has recently been initiated. We use the model to evaluate the effectiveness of areas closed in the NRA to protect sponge concentrations and to evaluate commercial sponge by-catch encounter thresholds used to indicate the presence of a VME in the same area. However, we feel the model has potential to address similar questions within the Canadian Exclusive Economic Zone (EEZ).

METHODS

DESCRIPTION OF MODEL INPUT DATA LAYERS

Fishing Effort and the Existing Fishing Area

NAFO is required to regulate the ecosystem impacts of bottom fisheries that have the potential to cause significant adverse impacts on vulnerable marine ecosystems (UNGA Res. 61/105). Among the actions called for in the FAO Guidelines for sustainably managing deep-sea fisheries and implementing UNGA Res. 61/105 (FAO 2009), is the mapping of existing bottom fisheries. In response, the NAFO Fisheries Commission has asked member states to submit maps identifying bottom fishing areas in the NRA, for the period 1987-2007, with trawl activity given priority. Details of the procedure used to produce a map of fishing effort are provided in NAFO (2009a). Ten member states provided bottom fishing coordinates, with three also providing information on vessel speed. The portion of the dataset containing speed data (Japan, Portugal and Norway) was filtered to include data only when the vessel was travelling between 1.0-4.0 knots. The point dataset used in our simulation model was derived from an interpolated (krig) 2.5 x 2.5 nm raster (NAFO 2009a). Each cell of the raster was converted to a central point within each cell and the cumulative effort value for each raster cell was extracted to the point. This value is an estimate of the number of times vessels would frequent a single 2.5 nm^2 cell

from at least two separate years between 1987 and 2007 (Figure 1, NAFO 2009a). These point data were then re-transformed using kriging interpolation in ArcGIS 9.2 (ESRI Canada Limited) to create a raster of fishing effort cropped to the NAFO fishing areas in the NRA (Figure 2).

Sponge Biomass Distribution

Sponge by-catch records from the NRA were collected during the multispecies stock assessment surveys conducted by DFO, Newfoundland and Labrador Region, between 1995 and 2008. Sponges are recorded as "Porifera" in this data set with no further breakdown by species. There were 278 records of sponge from these surveys. All of the surveys were from a stratified random design by depth and used a Campelen 1800 shrimp trawl with rock hopper foot gear (McCallum and Walsh 1996). Tow duration was 15 minutes and followed a depth contour producing an average tow length of 1.4 km (Edinger et al. 2007).

Using these data, a standardized weight raster was created using the "Inverse Distance Weighted" (IDW) interpolation tool in the "Spatial Analyst" extension of ArcGIS 9.2. The IDW tool recognizes that points close together are more alike than those far apart. By using the measured values surrounding the prediction location, IDW assumes that each measured point has a local influence that diminishes with distance. It weights the points closer to the prediction location greater than those farther away, hence the name inverse distance weighted.

The actual catch weights from each tow were standardized to kg/km prior to running the model by dividing the total catch/tow by the sea floor length of the tow using the General Bathymetric Chart of the Oceans (GEBCO; IOC, IHO and BODC 2003). However, in this area and with the resolution available with GEBCO, line length was influenced by less than 3% (100 m over 37 km) and so this function was not applied to avoid falsely distorting the data. Should high resolution multibeam imagery become available, it would be useful to incorporate bathymetry into the trawl distance particularly in areas of high slope. Running the IDW tool using the settings described in Figure 3, resulted in a raster output representing sponge biomass in kg/km as caught with Campelen trawl gear (Figure 4A and B). This raster is presented using raw data (Figure 4A), as well as with log transformed data (Figure 4B) to illustrate the heterogeneity at the lower end of the by-catch weight range.

The IDW tool input settings include the "Input Point" dataset and the field to be interpolated ("Z value field" – Weight in kg). The "Power" controls the significance of surrounding points on the interpolated value (a higher power results in less influence from distant points). It can be any real number greater than zero, but the most reasonable results will be obtained using values from 0.5 to 3 (the default is 2). The "Search Radius Type" is "Fixed" with no "Minimum Number of Points" and the "Distance" of the search radius set at 25,000 m. The "Output Cell Size" is set at the default, which is the shorter of the data extent values (width or height) divided by 250.

DESCRIPTION OF THE MODEL

We have developed a simulation model which provides a representation of the essential characteristics of real-world commercial fishing sponge by-catch in the NAFO Regulatory Area, which can be used to evaluate management actions and to predict future behaviour under a variety of different conditions (gear types, fishing behaviour, trawl duration, stop rules, etc.). The process of developing any simulation model involves defining the situation or system to be analyzed, identifying the associated variables, and describing the relationships among them as accurately as possible. In the present application, we have defined the length of commercial fishing trawls as 37 km, which is a standard trawl distance in the commercial Greenland halibut (turbot) fishery (Bill Brodie, DFO, Newfoundland Region, pers. comm.). However, this distance

can be easily altered for other applications and is only used here to illustrate our methodology. It is our understanding that this trawl length is towards the upper limit of trawl lengths in commercial fishing practices. Compared with the trawl distance, differences in trawl width between the Campelen research vessel trawl and a commercial trawl is considered minor and has not been factored into the model at this stage.

Two versions of the model are presented. Model A (Figure 5) uses random start points and randomly oriented 37 km trawl lines (radiating to the periphery of a 25 km radius circle around the start position). The model then extracts the biomass under the trawl lines from the IDW sponge biomass by-catch raster (Figure 4) to give the total sponge by-catch in kg/37 km trawl.

In the second version of the model (Model B), we have incorporated knowledge of real-world fishing behaviour to weight the start position and orientation of the 37 km trawl lines towards the direction of maximum fishing effort. This model uses the fishing effort raster (Figure 2) described above and creates a trawl line travelling in the direction of the greatest sum of effort over the line.

In describing the model, we present the more complicated Model B first (Figure 6), as Model A (Figure 5) is a truncated version of Model B.

Model B: Start and Trawl Orientation Weighted by Fishing Effort

In this model simulation, trawl start locations and orientation are located within the fishing footprint using the underlying fishing effort raster (Figure 2) as a weighted probability distribution. The probability for each cell within the raster is calculated by: (value of cell) / (maximum value). As such, the raster can represent the directly estimated probabilities (range: 0-1), or can contain any range of numbers that represents the relative probability of occurrence between cells (http://www.spatialecology.com/htools/rndpnts.php).

No "ready-made" tool is currently available within the toolbox provided by ArcGIS 9.2 that can perform weighted random point generation to be incorporated within the model. The "Generate Random Points" tool from Hawth's Tools, part of a free downloadable ArcGIS extension, was used to create the points as described above prior to running Model B (http://www.spatialecology.com/htools/tooldesc.php).

Steps in Model B (Figure 6) are linked via arrows which dictate the direction of data products as they are generated. Steps in the model are symbolized to represent data inputs (blue boxes), tools (orange ovals), and outputs (tables, shapefiles, intermediate steps – green boxes). Step **A** of the model uses an "Add ID Field" tool to create a unique "Random Point ID" field that is required in subsequent steps of the model. Steps **B** and **C** create a 37 km circle around each point (N=100), which is then clipped and annealed to be confined to the boundaries of the footprint (Figure 7A). Step **D** then uses the "ET Polygon to Polyline" tool to convert the 100 polygons to polylines. This is necessary because Step **E**, which uses the "Create Buffer Stations" tool to place 180 equidistant points (placed at 2 degree or ~1295 m intervals) around the periphery of each buffer, will only add points to a line and not to the outline of a polygon (Figure 7B). Step **F** uses the "ET Spider Diagram Attributes" tool to connect each random point to all station points generated in Step **E**. This tool is set to exclude line lengths exceeding 37 km, thus eliminating lines from each random point which connect to station points of other buffers lying outside the optimal trawl length (Figure 7C). The next two steps create an ID field (**G**) and then calculate its value (**H**). Like Step **A**, these steps are necessary in subsequent stages of the model that require unique IDs to create joins between related datasets. The "Create Line Stations" tool (**I**) is then used to create equidistant (2500 m) points along the length

of each line generated from Step **F** (Figure 7D). At this point, the interpolated raster of fishing effort (Figure 2) is incorporated into the model (blue box under **J**). The "Extract Values to Points" tool is then used to pull the raster data value underlying the station points (**F**) into the attribute table of the points (**J**). The "Stats Table Effort Sum" tool (**K**) sums the extracted effort values for each point along individual spider lines. After steps **L** and **M,** which again add another field for subsequent joining, the "Calculate Max Effort" tool selects the maximum sum value of station points, representing only one value radiating from each random start point (**O**). Steps **N** and **P** then create temporary tables to join (**Q**) the text attributes from the list of station point sums radiating from each random point (**M**) and the numerical attributes from the output of the maximum of the station point sums (**O**). From these joined tables, a "Summary Statistics" tool is used to create a *.dbf table of the maximum station point value for each of the 100 random points (**R**). This table is then joined (**T**) with the temporary attributes table from the "Spider Lines" shape file (**H**) and then converted to a "Maximum Effort Trawl Lines From Each Start Position" shape file (**U**). This output represents 100 lines from 100 weighted random points following the direction of greatest effort (Figure 7E).

To estimate the total sponge by-catch observed along the line, station points are then placed at 500 m intervals along the final lines (**V**) and the values from the IDW interpolation of by-catch are extracted to each point (**W**) (Figure 7F). The "Summary Statistics" tool (**X**) is then used to calculate the mean of the by-catch (kg/km) from station points along each line radiating from the 100 random points. Temporary numerical (**Y**) and text (**Z**) attribute tables of the final lines are then joined (**AA**) and then converted via the "Copy Features" tool to a shape file, "Maximum Effort Trawl Line with Mean Sponge Catch (line)" (**AB**). The length of the line is then calculated (**AC**) and multiplied by the mean by-catch per line (**AD**)[1]. This calculated value (total catch) is then placed into the "Maximum Effort Trawl Line with Mean Sponge (Catch)" field created during step **AD.** The final output, "Maximum Effort Trawl Line with Total Sponge (Catch)" contains 100 lines with trawl length, calculated tow by-catch rates, and total by-catch per tow (**AE**).

Preliminary runs of Model A revealed a number of inherent issues within the Model Builder ArcGIS extension. While the individual tools work well when applied outside of the model frame work, stringing the tools together slowed down the processes so only 100 start locations could be run at any one time. When run in ArcInfo, the model would occasionally develop a "schema lock" usually associated with the files used or generated by the model, being used simultaneously by another program (e.g., ArcCatalog). When this happened, the only way to make the model run again was to close all programs and restart. In addition, during most runs a single step (Step **L** – add field tool) would completely halt its progress. A number of fixes of varying success were introduced to the model and the computer to overcome these limitations.

The speed of the model was improved by creating a scratch output environment for intermediate steps in the model. By running the model in ArcCatalog instead of ArcInfo, the "schema lock" problem was dramatically reduced to the point where the model could be run successfully at least 15 times consecutively without error. Additional random access memory was also added to the computer (from 2 to 4 gb) and used as a virtual RAM disk drive where all model steps were run. To fix the stall at Step **L** it was realized through an online forum provided by ESRI that dual core computers can sometimes confuse certain tools (http://forums.esri.com/Thread.asp?c=

[1] Previous iterations of the model used the "Surface Length" tool from the 3D Analyst Extension of ArcGIS to calculate the line length. This tool utilizes an underlying bathymetry raster (e.g., General Bathymetric Chart of the Oceans - GEBCO) to estimate the distance on the ground taking into account depth (z). Including z for a 37 km line (even in a high slope environment) increased the total line length by only 100m. For this reason, the tool was not included in the final version of the model. If higher resolution bathymetry becomes available (i.e., multibeam) then this tool could improve the tow length calculation.

93&f=1727&t=213148). Thus, by directing the affinity of ArcCatalog to only one CPU (Windows Task Manager>Processes>right click on ArcCatalog>Set Affinity>click checkmark of 1 CPU) Step **L** worked flawlessly.

With these solutions implemented, the model is currently capable of running 100 random points at any one time. For each scenario, the model was run 15 times using randomly generated start locations within the confines of the fishing footprint for each scenario. The outputs from a single scenario (15 polyline shapefiles with 100 lines each) are then amalgamated using the ESRI "Append Data Management" tool, which is a final step not incorporated into the final version of the model. The result is a single file of approximately 1500 polylines.

Model A: Random Start and Trawl Orientation

In Model A the start points and orientation are both random. Because many of the steps necessary to create lines of standard length and random orientation utilize the Hawth's tools extension (which cannot be incorporated into Model Builder), Model A is essentially a truncated version of Model B. Many of the steps from Model B (**A – U**) are involved with determining the orientation of the trawl line by calculating the sum of effort for each line and choosing the line radiating from the weighted random centre point with the greatest sum of effort. These steps are removed in Model A and replaced by a data input polyline shapefile ("Random Lines") consisting of 3000 lines of random start location and orientation. While not illustrated in the model, a number of steps were taken to create the polyline input:

1. 3000 points were generated within the bounds of the fishing footprint for each scenario using "Generate Random Points" under the Sampling Tools subheading of Hawth's tools ArcGIS extension (Figure 8A).
2. The ID field is then calculated (=FID+1) to create a unique consecutive ID for each point (1-3000).
3. 3000 buffer polygons are created using the ESRI "Buffer Tool" (Figure 8B).
4. Utlizing the ET Geowizards "Polygon to Polyline" Conversion tool, the buffer polygons generated in Step 2 are converted to polylines (Figure 8C).
5. Again utilizing the ESRI "Buffer" tool, a 100 m buffer is placed around each line (Figure 8D).
6. To generate the line end point at a random orientation from the start point, the "Generate Random Points" tool from Hawth's tool ArcGIS extension was used to generate a single random point in each polyline buffer from Step 5. This creates a point ~37 km (±100 m) from the random start point generated in Step 1 (Figure 8E).
7. The consecutive ID from the start point matches with the consecutive ID from the end point. The next Step involves amalgamating the random start and end points using the ESRI "Append Data Management" tool.
8. Using the appended data set which consists of 6000 points (3000 start and 3000 end points), the ET Geowizards "Points to Polyline" Conversion tool is used to create a polyline shape file with 3000 lines of random start and orientation within the scenario's fishing footprint.
9. The polylines from Step 8 are then clipped to the dimensions of the fishing footprint for each scenario using the ESRI "Clip (Analysis)" tool (Figure 8F).

It is the 3000 clipped, randomly oriented polylines that are used as the input for Model A. The final steps of Model A are identical to those from Model B. Station points are placed along the line at 500 m intervals, the data from the IDW interpolation raster of by-catch are extracted to each point, the mean by-catch per line is then calculated from the extracted data, which is then multiplied by the total line length to calculate total by-catch per line. Unlike Model B, Model A

had a number of lines much shorter than 37 km as more random lines crossed the fishing footprint and were clipped. The data was subsequently filtered by using the ESRI "Select by Attributes" tool to only include polylines greater than 32 km in length. Once complete, the final dataset was truncated to include only the first 1500 records.

Including Management Decisions in the Model Simulations

Closed Areas

The NAFO Fisheries Commission at their 2009 meeting in Bergen, Norway (NAFO 2009b), closed 11 areas covering 2500 square nautical miles to bottom fishing activities to protect sponge grounds, sea pen fields and large gorgonian corals, as well as black coral habitat within the fishing footprint of the NRA (Figure 9). Previously, the Fisheries Commission established a Coral Protection Zone in a large area in NAFO Division 3O, which is closed to all fishing activity involving bottom contact gear until 2012, when the closure will be reviewed (NAFO 2007, Figure 9). In order to evaluate the effect of these closures on the simulated sponge by-catch, Models A and B were each run under two scenarios: 1) simulated trawl lines within the fishing footprint, and 2) simulated trawl lines within the fishing footprint and outside of the closure areas:

Model A ***Scenario 1.*** Generate random points within the NRA fishing footprint with random orientation.

Scenario 2. Generate random points within a modified NRA fishing footprint which excludes the newly ratified NAFO closure areas (VMEs) for both coral and sponge (NAFO 2009b).

Model B ***Scenario 3.*** Generate statistically weighted random start points within the NRA fishing footprint, with trawl orientation based on the maximum cumulative effort.

Scenario 4. Generate statistically weighted random start points within a modified fishing footprint which excludes the newly ratified NAFO VMEs for both coral and sponge falling within the NRA fishing footprint. As with Scenario 3, trawl orientation is based on maximum cumulative effort.

Figure 10 shows the final line placement and orientation for each of the scenarios described above.

Encounter Thresholds

Apart from the closed areas described above, the only protection to sponges inside the fishing footprint is the "encounter" or "move-on" rule. UNGA resolution 61/105 requires "members of the regional fisheries management organizations or arrangements to require vessels flying their flag to cease bottom fishing activities in areas where, in the course of fishing operations, vulnerable marine ecosystems are encountered, and to report the encounter so that appropriate measures can be adopted in respect of the relevant site." Paragraph 7 of the Interim Measures likewise mandates that participants "[r]equire that vessels flying their flag cease bottom fishing activities within five (5) nautical miles of any site in the Area where, in the course of fishing operations, evidence of vulnerable marine ecosystems is encountered, and report the encounter, including the location, and the type of ecosystem in question, to the interim Secretariat so that appropriate measures can be adopted in respect of the relevant site. Such sites will then be treated in accordance with paragraph 6 above."

The NAFO Fisheries Commission at their 2009 meeting in Bergen, Norway (NAFO 2009b), adopted an encounter threshold of 800 kg sponge/commercial tow but recognized that there was no scientific basis for this threshold value. It has asked the NAFO Scientific Council to comment on this issue at its June 2010 meeting.

Data from observers on commercial fishing vessels in the NRA and elsewhere have a number of deficiencies that prevent its use in quantitative applications, such as the evaluation of threshold levels. This information is useful in recording the presence of sponges, but the biomass associated with the by-catch and the null records are considered to be unreliable overall (NAFO 2008). Use of simulation models can estimate the probable commercial by-catch of sponges in the NRA and their location, and encounter thresholds can be evaluated against the simulated sponge by-catch distribution. These estimates can then be used to undertake a preliminary assessment of the risk of Significant Adverse Impact (SAI) of fishing activities on sponges, considering aspects of their life history, recovery ability etc.

EVALUATION OF MODEL OUTCOMES

Each model Scenario was run through 1500 iterations in order to produce stable model outcomes. In order to evaluate whether 1500 iterations were sufficient to achieve this objective, a cumulative moving average (CA) or "running" average was applied. A *CA* is an unweighted average of the sequence of i values $x_1, \ldots, x_i$ up to the last value:

$$CA_i = \frac{x_1 + \cdots + x_i}{i}.$$

The last data point in the series ($i = 1500$) will produce a *CA* equal to the final average.

The 1500 simulated sponge by-catch data were sorted in descending order for each Scenario and paired *t*-tests were applied to pairs of Scenarios (1 and 2, 1 and 3, 2 and 4, 3 and 4). In this test, the difference between each pair of data is calculated and the test calculates the probability that the mean of the difference among pairs is 0.

The location of the simulated trawl lines underlying the data were examined in detail by Model type.

RESULTS

Sponge by-catch weight for 1500 simulated trawl lines were run under each of the Scenarios described above. The cumulative moving (running) averages produced from these lines are illustrated in Figure 11. All four Scenarios showed high fluctuations over the first 100 iterations but stabilized after about 800 iterations. We conclude that the 1500 iterations used to develop our simulated trawl sponge by-catch are sufficient to evaluate management decisions.

The final averages for the four Scenarios show that the simulated average sponge by-catch from the Model A outputs (random start positions and orientations) are lower than those from the Model B outputs (weighted random start positions and weighted orientation), and that for both Models, simulated average sponge by-catch was lower when the trawl lines were excluded from the areas closed to protect coral and sponge (Figure 11), indicating that this management decision is having an influence on both types of modelled fishing scenarios. These results show

that the model is sensitive to both the underlying IDW sponge by-catch raster and to the fishing effort raster.

The simulated trawl lines produced total sponge by-catch estimates which were ranked as Scenario 3>Scenario 4>Scenario 1>Scenario 2, with corresponding total sponge by-catch of 2,823 mt, 2,066 mt, 1,574 mt, and 755 mt, respectively. Excluding the simulated trawl lines from the closed areas had a greater effect on the Model A (random) outputs than on the Model B (weighted by fishing effort) sponge by-catch outputs, with the former producing a 52% reduction in by-catch and the latter a 28% reduction.

All scenarios showed that nearly 40% of the simulated sponge by-catch over the 37 km trawl lines weighed less than 2 kg (range 38.4 for Scenarios 3 and 4 to 41.3 for Scenario 2), with approximately 47% of the simulated by-catch less than 10 kg (range 46.3 for Scenario 1 to 49.2 for Scenario 2).

The maximum values of simulated sponge by-catch for a single 37 km trawl line for Scenarios 1 to 4 were: 54 mt, 51 mt, 76 mt and 75 mt. The volume occupied by the sponges to produce these weights should be considered relative to the volume of the net. In real-world fishing operations (i.e., Scenario 4), it is unlikely that such large hauls would be made. Typically the captain would haul back the net once it was detected that the net was not fishing properly. If the level of by-catch under which this occurs could be estimated then stop-rules could be incorporated in the future to trim off unrealistic outputs.

Paired t-tests showed significant differences ($P<0.0001$) amongst all pairs of Scenarios (1 and 2, 1 and 3, 2 and 4, 3 and 4). Graphical output from these analyses are illustrated in Figure 12 for two Scenario pairs (1 and 2, 3 and 4) in order to illustrate where differences were occuring due to the area closures for coral and sponge. For Model A, the difference between Scenarios 1 and 2 is greatest from about 10,000 to 20,000 kg, with another large difference at about 40,000 kg (Figure 12). For Model B, the greatest difference occurs at about 15,000 to 20,000 kg, with larger simulated by-catch under Scenario 3 than Scenario 4 (simulated lines restricted from closed areas). For these Scenario pairs, the differences become less pronounced around 35,000 to 40,000 kg, but appear again between 40,000 and 50,000 kg, and at about 65,000 kg (Figure 12).

The simulated sponge by-catch frequency distribution for the 1500, 37 km simulated trawl lines from each of the four Scenarios are illustrated in Figure 13, and for Scenarios 1 and 2 under Model A (Figure 14) and Scenarios 3 and 4 under Model B (Figure 15) separately. The differences in the scale of the x-axis (simulated total catch) should be noted when comparing the relative heights of the peaks in the frequency distribution. Five areas are highlighted (labelled A to E on the graph) for further evaluation. For simulated sponge by-catch in the range of 10 to 70 kg per 37 km tow (labelled A), the weight is higher for the Model B (weighted) outputs than for the Model A outputs (random). For simulated weights in the range of 100 kg (labelled B) the Model A (random) outputs are much greater than those generated by the Model B (weighted outputs). At about 700 kg (labelled C), the effect of the closures can be seen in the Model A (random) outputs (Figures 13 and 14). Between 800 and 2,000 kg (labelled D), all model outputs show a peak, and for the very large simulated sponge by-catch at the tail end of the distribution (over 8,000 kg), all Scenarios show divergent patterns (labelled E).

The location of the simulated trawl lines underlying the data for each of these five areas are examined in detail by Model type with reference to the management decisions detailed above.

SIMULATED SPONGE BY-CATCH LESS THAN 800 KG/TOW

NAFO currently uses 800 kg of sponge per tow (nonspecified length) as the threshold levels for commercial fisheries encountering a sponge-dominated VME, requiring the vessel to move away. The majority of the simulated sponge by-catch falls below 800 kg under all four Scenarios: 89.3% Scenario 1, 94.3% Scenario 2, 89.5% Scenario 3, and 91.5% Scenario 4. The effect of the closures increases the number of by-catch records in this weight category under both Model A and Model B.

Simulated Sponge By-catch of 10 – 100 kg

Approximately 33.6% of the sponge by-catch records for each Scenario fall between 10 and 100 kg (range 31% Scenario 1 to 36.7% Scenario 4). The simulated sponge by-catch for trawl lines generated under Model A in this weight range showed little difference between Scenario 1 and Scenario 2, the Scenario which introduced the effect of the area closures (Figure 14). However, data generated under Model B over the same weight range showed larger differences in the outputs between Scenarios 3 and 4, with Scenario 4 showing a reduced simulated sponge by-catch (Figure 15, A). The position of the trawl lines which produced simulated sponge by-catch in this range under Model B is illustrated in Figure 16. The differences in frequency distribution cannot be attributed to the effects of the closure since the locations of the simulated trawl lines under both Scenarios are not influenced by them (Figure 16). The simulated trawl lines for both Scenarios produce by-catch of sponge in this weight range in areas at the canyon heads, in Flemish Pass north of the closure area, on Sackville Spur south and west of the closure area and on Flemish Cap itself (Figure 16). Although these areas appear green on the IDW raster (Figure 4), that is a product of the bins used to visualize the catch and the sponges are actually more abundant in these areas than it appears on the biomass raster, although catches are still relatively low. A log transform of the IDW interpolation raster data (Figure 4B) reveals the spatial heterogeneity of the by-catch data and highlights the lower by-catch values otherwise not immediately evident with the un-logged data illustrated in Figure 4A. By excluding lines from entering the closed areas, more lines are forced into the remaining area which is reflected in the comparative increase in lines for Scenario 4 for this weight range (Figure 16).

Differences between Model A and Model B outputs are most prominent in the 30-40 kg range. Figure 17 shows the location of the simulated trawl lines producing sponge by-catch in this range for Model A and Model B. Under Model A the randomly generated start and end points for each simulated trawl line fall over the low density sponge areas in the IDW raster. Weighting the location of the simulated trawl lines by fishing effort under Model B concentrates the lines in areas where sponge density is higher, that is in Flemish Pass and west of the Sackville Spur closure, and also greatly increases the number of records in these areas (Figure 17).

Simulated Sponge By-catch of 100 – 800 kg

Sponge by-catch records for each Scenario differ among Models in the number of records falling between 100 and 800 kg. Under Model A (random), 12% of the by-catch is within this range under Scenario 1 and 14% under Scenario 2. In contrast, under Model B (weighted), only 6% and 8.3% of the records fall within this range under Scenario 3 and 4, respectively. This indicates that including information from the fishing effort raster has a large influence on the results in this by-catch weight range (see Figure 13).

The simulated sponge by-catch for trawl lines generated under Model A showed little difference in by-catch through the range of 100-800 kg between Scenarios 1 and 2, which introduced the

effect of the area closures (Figure 14). The only exception is a small peak at about 700-800 kg where Scenario 2 produces larger by-catch than Scenario 1 (Figure 14, C). The difference in this area is due to in part to the low total number of trawl lines in this range (N=20), and the 14 data record difference amongst Scenarios. The location of those simulated trawl lines along the slope of Flemish Pass where sponge biomass is higher is also a factor (Figure 18).

Data generated under Model B showed some differences in the outputs between Scenarios 3 and 4 in catches in the range of 100-1,000 kg (Figure 15). The position of the trawl lines which produced simulated sponge by-catch in this range under Model B is illustrated in Figure 19. The effect of the closures increases the number of records in this by-catch range for Scenario 4 over Scenario 3, and these displaced trawl lines fall in the canyon heads and in Flemish Pass (Figure 19).

The greatest difference in this simulated by-catch range between Models A and B is localized to the 100-200 kg sponge by-catch range (Figure 13, B). Figure 20 illustrates the location of these simulated trawl lines under each model (combining data for Scenarios 1 and 2, and Scenarios 3 and 4). Under Model A (random), the data are generated from simulated trawl lines in Flemish Pass and the slopes of Flemish Cap, which are not found in to the same degree in the lines produced through Model B (weighted).

SIMULATED SPONGE BY-CATCH GREATER THAN 800 KG/TOW

Approximately 11% of the simulated by-catch records for both Model A and Model B are greater than 800 kg when the simulated trawl lines are only restricted to the fishing footprint (Scenarios 1 and 3). Further restriction of the lines so that they are not allowed to cross the closure areas (Figures 9, 10) reduces the percent of records within this range to 6% under Scenario 2 (random Model A) and 8.5% under Scenario 4 (weighted Model B).

The simulated sponge by-catch for trawl lines shows two peaks in the range greater than 800 kg with some difference in by-catch between Scenarios 1 and 2 (Figure 14, D and E). The locations of the trawl lines producing the by-catch associated with the first peak (1,000 to 10,000 kg) under Model A, Scenarios 1 and 2 are illustrated in Figure 21. Over this by-catch range the area closures have a strong effect in reducing the by-catch under Scenario 2, both through fewer by-catch records in this weight range and through the exclusion of trawl lines from the high density areas, particularly through the closures in Flemish Pass (Figure 21). Under Model A, the very large simulated by-catch over 10,000 kg, associated with the peak labelled E (Figure 14) shows the greatest divergence between the Scenarios and the by-catch is even more strongly influenced by the area closures on Sackville Spur and Flemish Pass (Figure 22).

The locations of the trawl lines producing the by-catch associated with the 1,000 to 10,000 kg range (Figure 15, D) under Model B, Scenarios 3 and 4 are illustrated in Figure 23. Here, the number of records for each Scenario is similar, but the Flemish Pass closure results in more records along Sackville Spur outside of the closure area under Scenario 4 (Figure 23). Differences between Scenarios 3 and 4 greater than or equal to 10,000 kg (Figure 15, E) show two peaks in by-catch under Scenario 3 that are not seen under Scenario 4 (Figure 15, E). The first of these peaks is in the range of 10,000 to 20,000 kg and is influenced by the Flemish Pass closure excluding effort under Scenario 4, while the second of these peaks in the range of 30,000 to 40,000 kg of sponge by-catch is due to the effect of the Sackville Spur closure (Figures 24 and 25, respectively).

The greatest differences among Models in the simulated sponge by-catch over 800 kg occurs in by-catch between 30,000 and 70,000 kg (Figure 13). Figure 26 illustrates the location of these

simulated trawl lines under each model (combining data for Scenarios 1 and 2, and Scenarios 3 and 4). Under both models these very high sponge by-catch records are found at two locations (Figure 26), Sackville Spur and a canyon head on the Grand Banks eastern slope. Under the random model (Model A), there are relatively few simulated trawl lines in these areas, but in the model weighted by fishing effort (Model B), there are more simulated lines in both areas.

DISCUSSION

Simulation modelling of commercial sponge by-catch in the NAFO regulatory area has provided some useful insights into the effects of management decisions to protect sponges in this area. The area covered by the research vessel surveys is greater than that of the fishing footprint and it is clear that the highest concentrations of sponge are found outside of the fishing footprint. However, there are large concentrations of sponge within the fishing footprint and with the area closures in place, and the location of simulated trawl lines weighted by fishing effort (Model B, Scenario 4), the total by-catch in 1500 trawl sets was reduced by 28% from 2,823 mt (Model B, Scenario 3) to 2066 mt (Model B, Scenario 4). Scenario 4 most closely approximates real-world fishing practices in the NRA. Of those 2066 mt, 38% of the individual by-catch records were less than 2 kg, and 91.5% of the records were less than 800 kg, the current encounter threshold for sponge.

Of the 8.5% of the records over 800 kg, most of these are found adjacent to the Sackville Spur sponge closure or the Flemish Pass area closure, and along the canyon heads of the Grand Banks (Figure 27). Some of the largest catches are just outside of the Sackville Spur area closure. These large catches may be inaccurate as the IDW spatial model may be over interpolating sponge biomass distribution in this area. In 2009, two benthic video transects were made on Sackville Spur running from about 1500 m to 1200 m depth and extending from the closed area into an area of high fishing effort. Preliminary assessments of the video indicate that the sponge grounds end sharply at about 1400 m while the fishing effort is generally shallower than 1200 m. Figure 28 illustrates the sponges in the sponge grounds at 1500 m and the type of habitat typical of the fished areas at 1200 m. If the boundaries are more abrupt than those of the IDW interpolation then these very large catches would not be taken in this area. The areas highlighted in Figure 27 should be re-examined to determine whether the current closure boundaries are sufficient to protect the sponge grounds. It is also important to note that in real-world fishing operations it is unlikely that such large sponge by-catch would be taken as the captain would haul in the net once it was determined that it was not fishing properly. As noted previously, stop-rules could be incorporated into the model to reflect this behaviour.

Reducing the encounter threshold from 800 kg to 100 kg/37 km tow would only affect a further 8% of the simulated by-catch records and protect sponges at the canyon heads of the Grand Banks and in the slope waters of Flemish Pass (Figure 19). A reduction from 800 kg to 50 kg/ 37 km tow would affect about 17% of the simulated by-catch records while a further reduction to 10 kg/37 km tow would affect 45%. Encounter thresholds of 10 kg or less would be met in most areas of high slope and in large portions of Flemish Cap and the Grand Banks.

The simulation model can also be used to estimate the amount of sponge removed from the fishing area. For Scenario 4, 1373 simulated 37 km trawl lines produced sponge by-catch less than or equal to 800 kg, the current encounter threshold. This represents 91.5% of the total number of simulated by-catch records for this Scenario. These records sum to approximately 64 mt of sponge. Reducing the encounter threshold to 100 kg of sponge/37 km tow would result in removals of approximately 22 mt. These values could be used to assess significant adverse impact if further information on species composition and associated biological traits were

known. Further, estimates of indirect effects of fishing (including modelling sponge catchability or retention factors) could be made using the information on the percentage of trawls involved and their location.

IMPROVING THE INFORMATION CONTENT OF THE SIMULATION

Weighting simulated trawl lines by fishing effort (Model B) has a pronounced effect on the results when compared with a random model (Model A). Here we used a generalized fishing effort raster combining location of all bottom trawl effort (NAFO 2009a), but this could be improved by providing similar information for different trawl types and/or fisheries, and by using data from more recent time frames.

We have used fishing effort to represent fishing behaviour but further information on commercial fishing practices could also be incorporated into the model. For example, if the fleet is known to fish in a certain way relative to depth or slope, the model can be adapted to weight the simulated lines according to those practices. Equally, if there is a maximum catch that could be expected due to physical characteristics of the gear or to decision making at sea, then stop rules could be included to trim the data so that the theoretical maximum catch is closer to the realized maximum catch.

An ideal set of required data is:

1. Sponge by-catch from research vessel surveys.
2. Species composition of the sponge by-catch including spatial distribution.
3. Accurate bottom bathymetry, particularly in high slope areas or on rough bottoms.
4. Accurate information on fishing behaviour (e.g., effort, tow direction, maximum catch).
5. Accurate estimate of trawl line dimensions (width and length).
6. Estimates of indirect effects of the fishing operation (gear retention relative to density on bottom, indirect damage).

However, we have been able to illustrate the methodology using only requirements 1, 4 and 5, which are the basic data inputs. Further research using this simulation model should focus on improving the quality and quantity of the required data.

REFERENCES

Edinger, E., Baker, K., Devillers, R., and Wareham, V. 2007. Coldwater corals off Newfoundland and Labrador: Distribution and fisheries impacts. WWF-Canada, Toronto, Ontario, Canada, v + 41 pp.

FAO. 2009. Report of the technical consultation on international guidelines for the management of deep-sea fisheries in the high seas. Rome, 4–8 February and 25–29 August 2008, 73 pp. ftp://ftp.fao.org/docrep/fao/011/i0605t/i0605t00.pdf

IOC, IHO and BODC, 2003. Centenary Edition of the GEBCO Digital Atlas, published on CD-ROM on behalf of the Intergovernmental Oceanographic Commission and the International Hydrographic Organization as part of the General Bathymetric Chart of the Oceans, British Oceanographic Data Centre, Liverpool, UK.

McCallum, B.R., and Walsh, S.J. 1996. Groundfish survey trawls used at the Northwest Atlantic Fisheries Centre, 1971 to present. Serial No. N2726. NAFO Scientific Council Research Document Doc 96/50, 18 pp.

NAFO. 2007. Report of the General Council. 29th Annual Meeting, 24-28 September 2007, Lisbon, Portugal. NAFO General Council Document 07/5, Serial No. N5478, 73 pp.

NAFO. 2008. Report of the NAFO Scientific Council Working Group on Ecosystem Approach to Fisheries Management (WGEAFM). NAFO Scientific Council Summary Document 08/10. Serial No. N5511, 70 pp.

NAFO. 2009a. Delineation of existing bottom fishing areas in the NAFO Regulatory Area. Serial No. N5676. NAFO Scientific Council Summary Document 09/21, 9 pp.

NAFO. 2009b. Report of the Fisheries Commission and its Subsidiary Body (STACTIC). 31st Annual Meeting, 21-25 September 2009, Bergen, Norway. NAFO Fisheries Commission Document 09/21, Serial No. N5735, 90 pp.

FIGURES

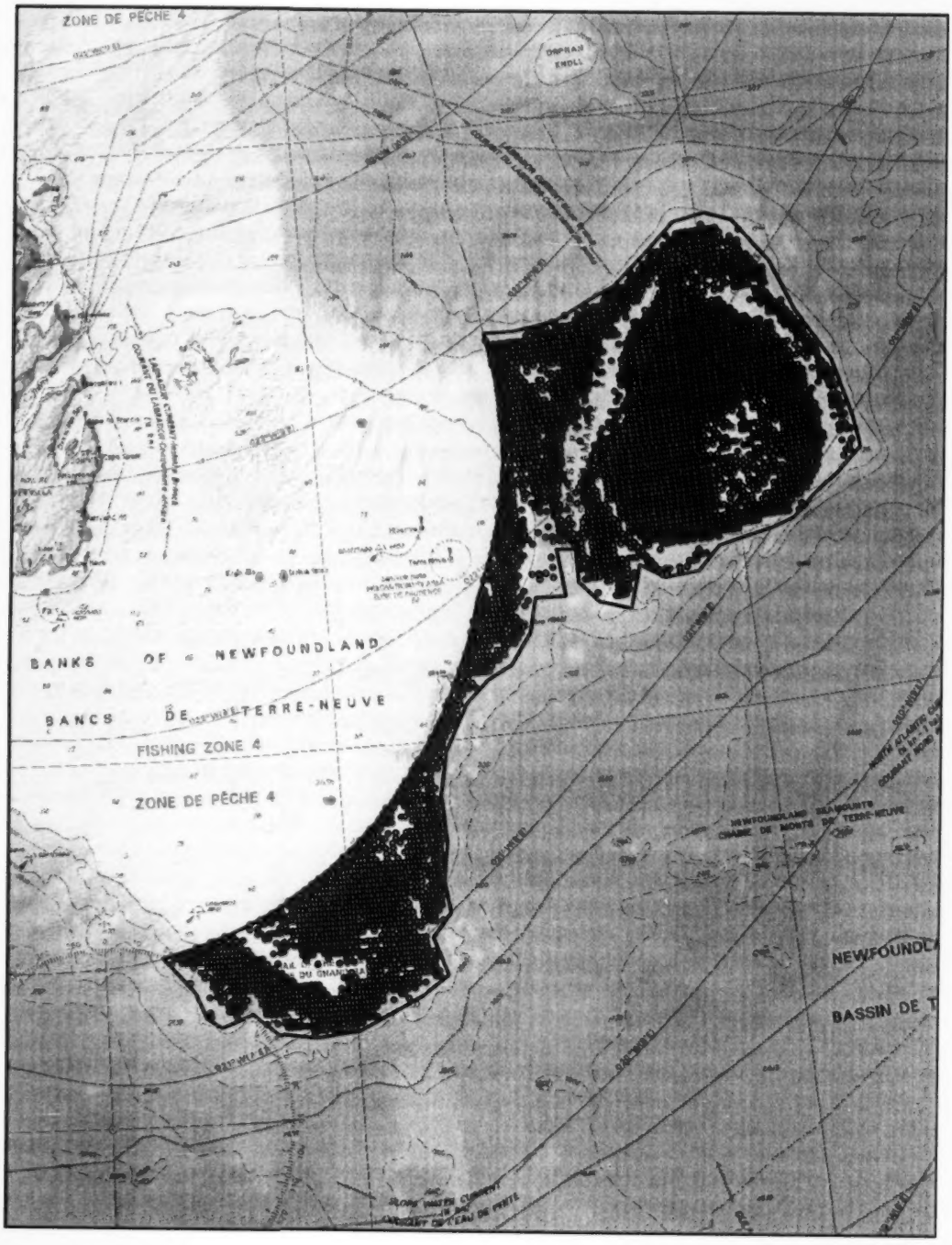

***Figure 1**. Location of the 2.5 nm^2 point data of fishing effort extracted from the effort raster provided by NAFO, clipped to the fishing footprint as identified in NAFO (2009a).*

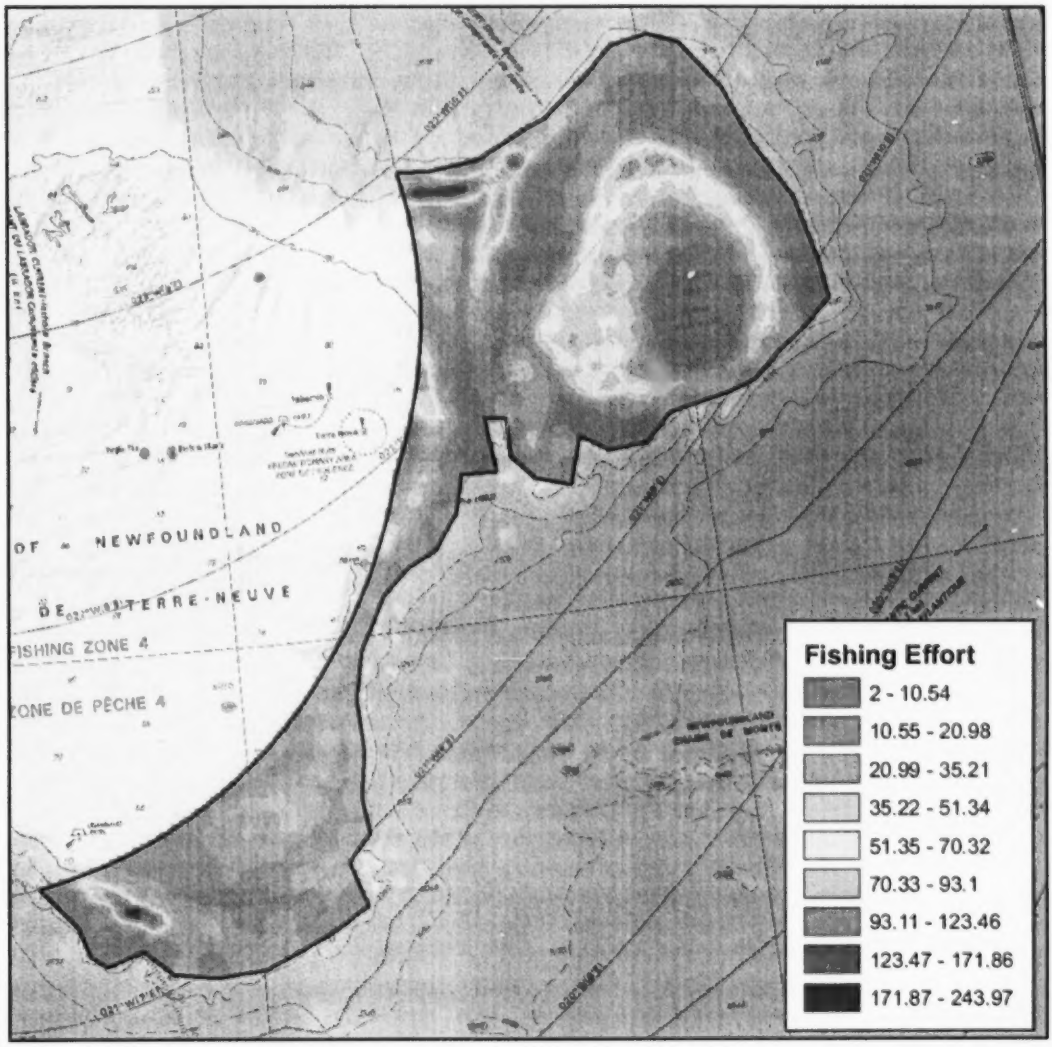

***Figure 2**. ArcGIS kriging interpolation of the fishing effort point data shown in Figure 1, clipped to the NAFO Regulatory Area fishing footprint. Fishing effort is scaled by the number of vessels per unit area (NAFO 2009a).*

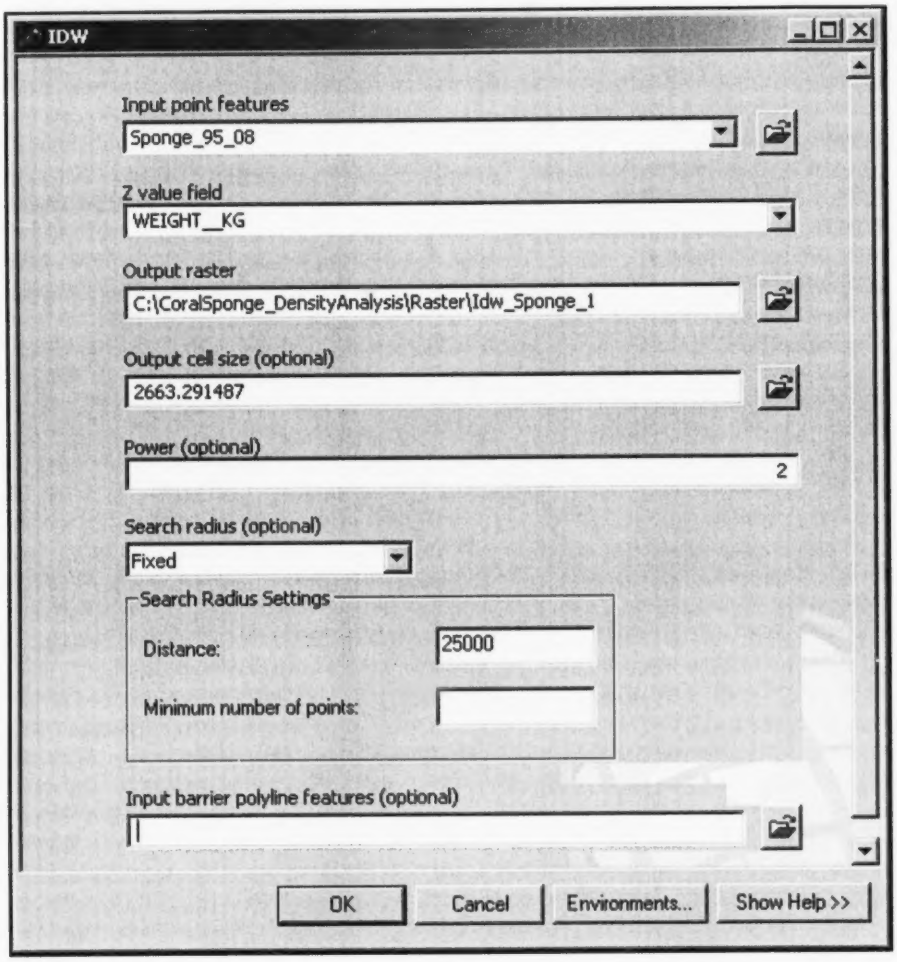

***Figure 3**. Inverse Distance Weighted (IDW) tool settings used to create a raster of approximated sponge biomass distribution.*

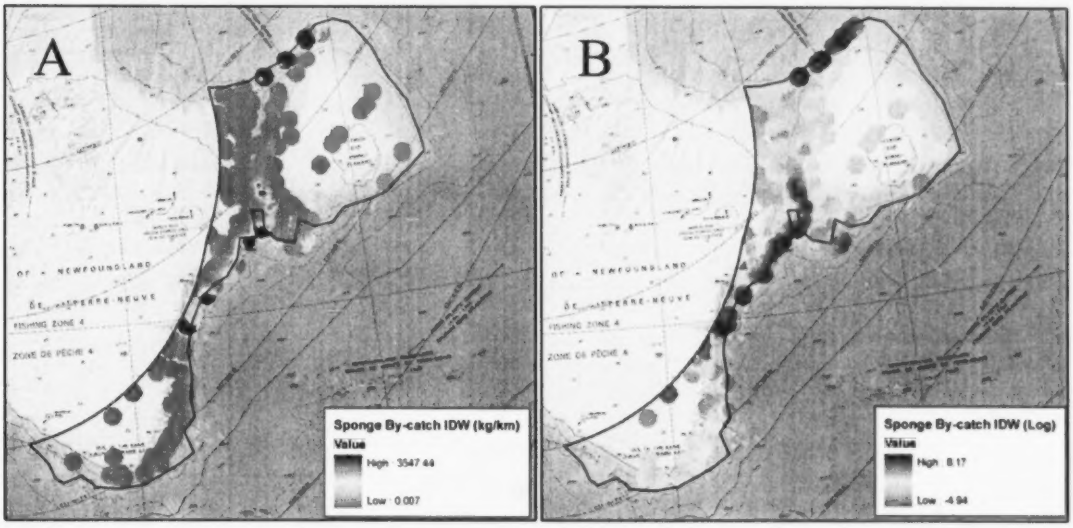

Figure 4. *Inverse Distance Weighting (IDW) interpolation of sponge biomass from DFO research vessel multispecies surveys using a Campelen trawl in the NAFO Regulatory area between 1995 and 2008. Panel A illustrates the data using a scale reflective of the actual by-catch values. Panel B illustrates the data using a log-transformation to show the spatial heterogeneity in the low to medium size by-catch.*

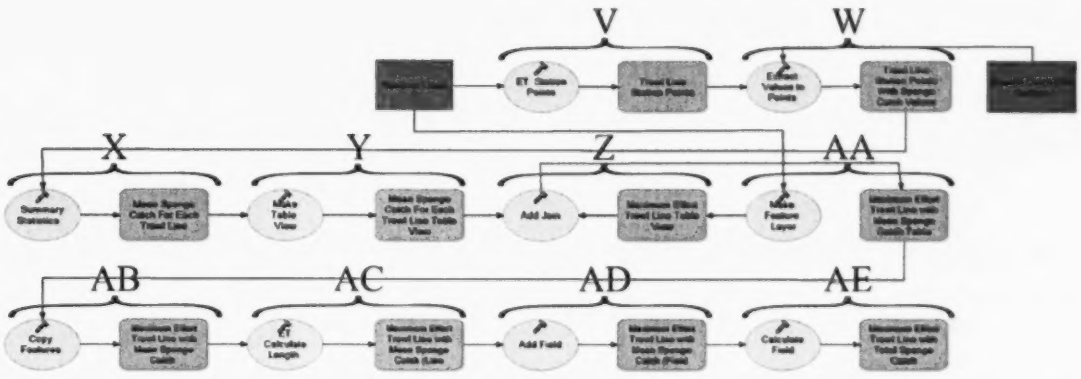

Figure 5. Model A. *The model created in ArcGIS 9.2 used to simulate commercial fishing sponge by-catch in the NAFO Regulatory Area using random start points and random trawl orientation. Details of the steps are provided in the text.*

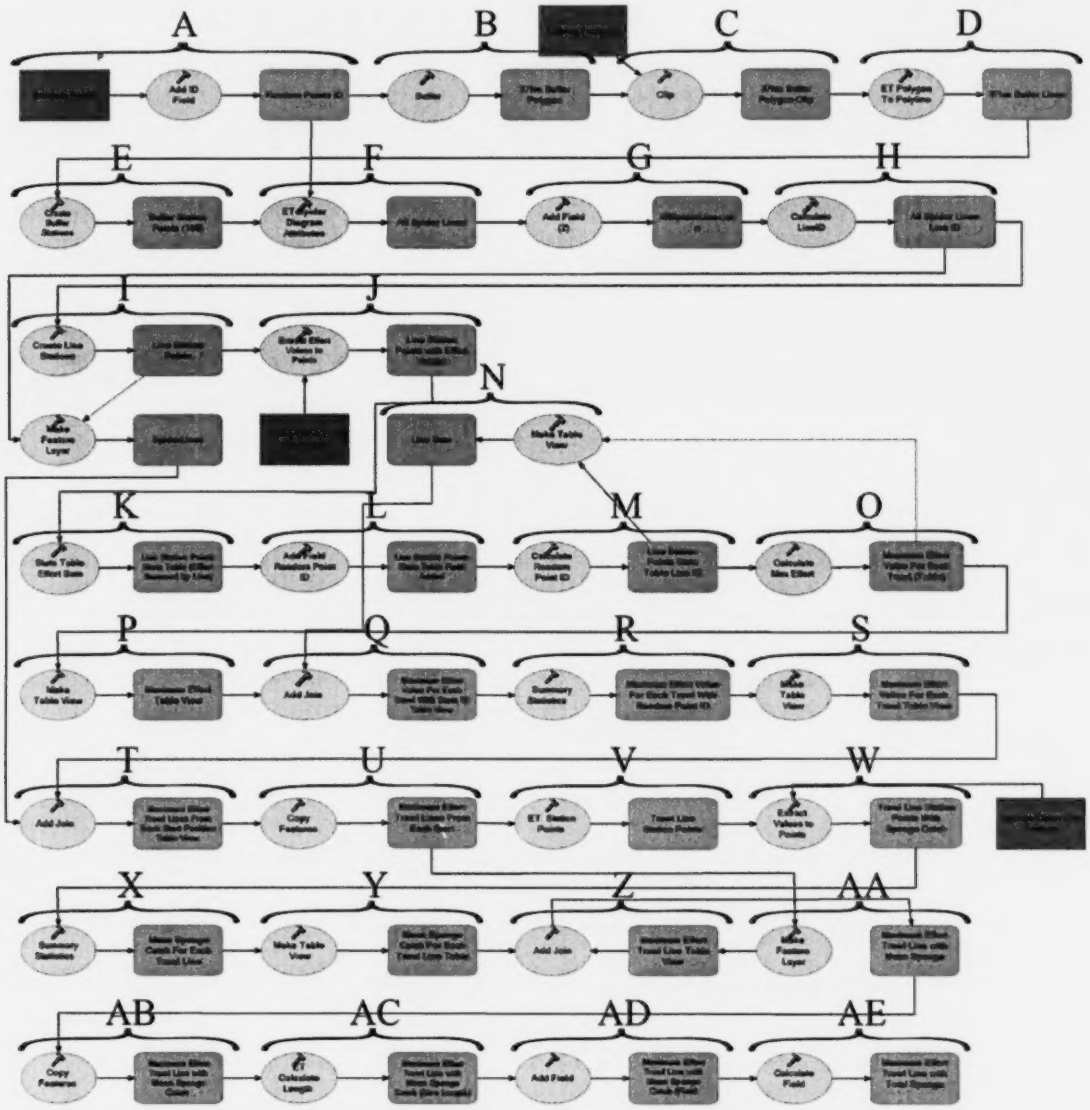

Figure 6. Model B. *The model created in ArcGIS 9.2 used to simulate commercial fishing sponge by-catch in the NAFO Regulatory Area using start points and trawl orientation weighted by information on fishing effort. Details of the steps are provided in the text.*

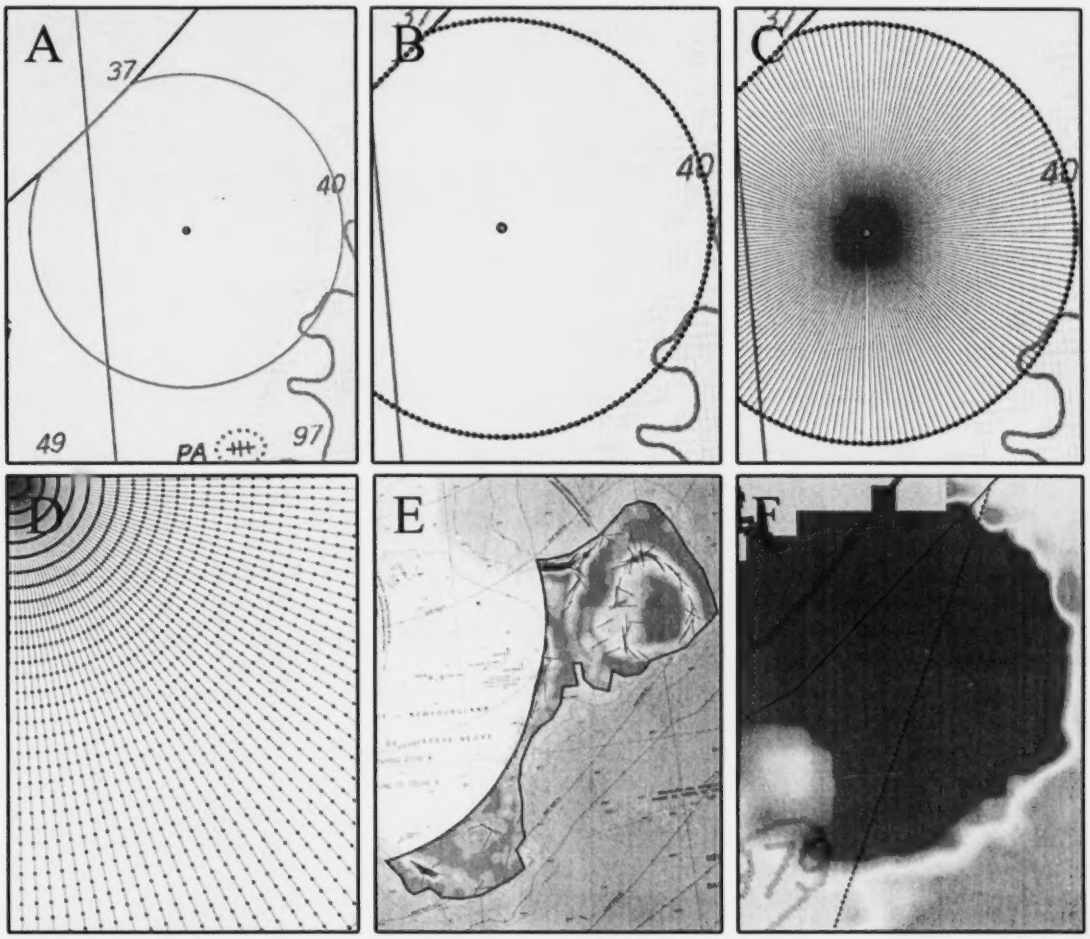

Figure 7. *Critical steps of the ArcGIS Models to estimate sponge by-catch in the NAFO Regulatory Area. A) Create a 37 km circle around each trawl start point, B) place 180 equally spaced "Station End Points" around the periphery of the circle, C) draw radiating lines from the random point to each "Station End Point", D) create "Station Points" at 2500 m intervals along each radiating line and extract and sum the effort data from the effort raster, E) choose 1 line radiating from each random point representing the direction of maximum sum of effort, and F) after creating "Station Points" of 500 m intervals along the selected line, extract by-catch values from the IDW interpolation to each point and calculate their mean which is then multiplied by the length of the line to determine sponge by-catch for each line.*

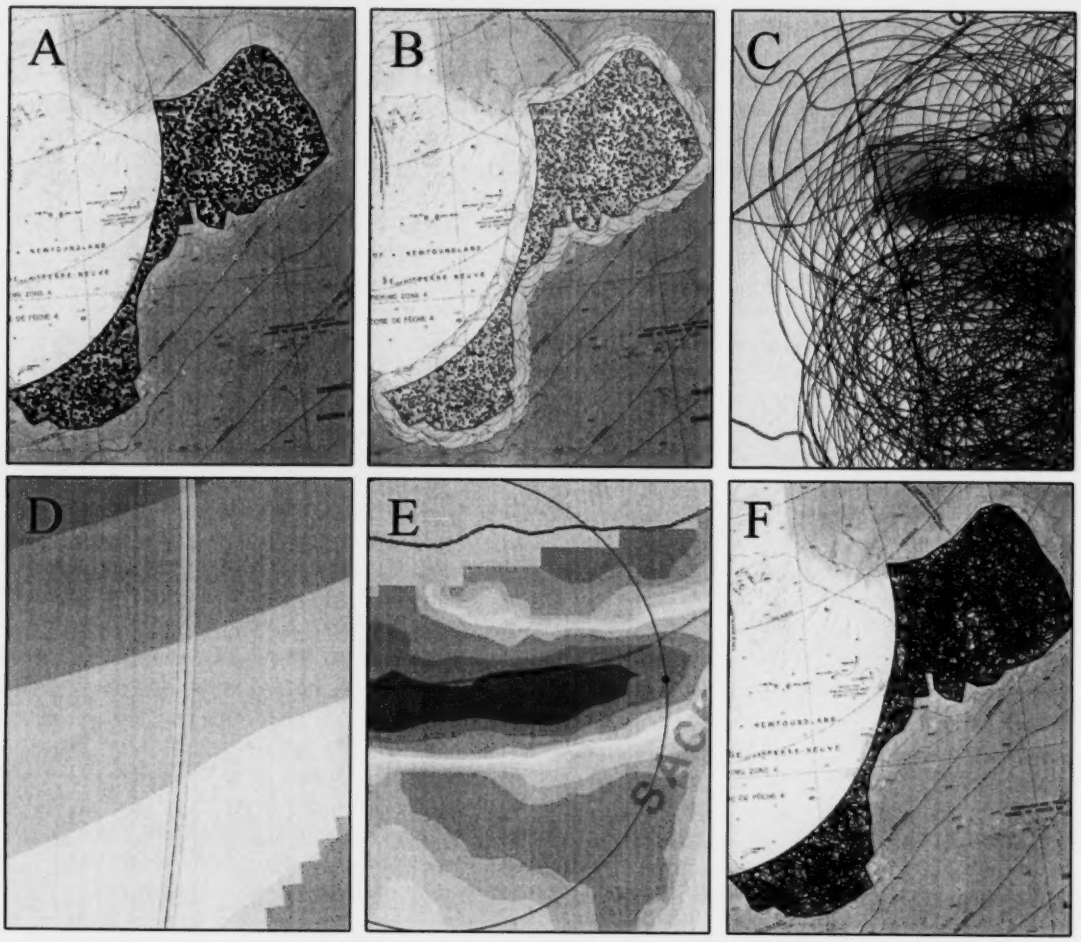

Figure 8. *Illustration of steps necessary to create the lines of random orientation data input for Model A (Figure 5). A) Create 3000 random points within the bounds of the fishing footprint, B) create 3000 circular polygons around each point, C) convert circular polygons to polylines, D) add a 100 m buffer around each line, E) create simulated trawl end point in 100 m buffer surrounding the polyline, and F) polylines created during step E are clipped to the dimensions of the fishing footprint for each scenario.*

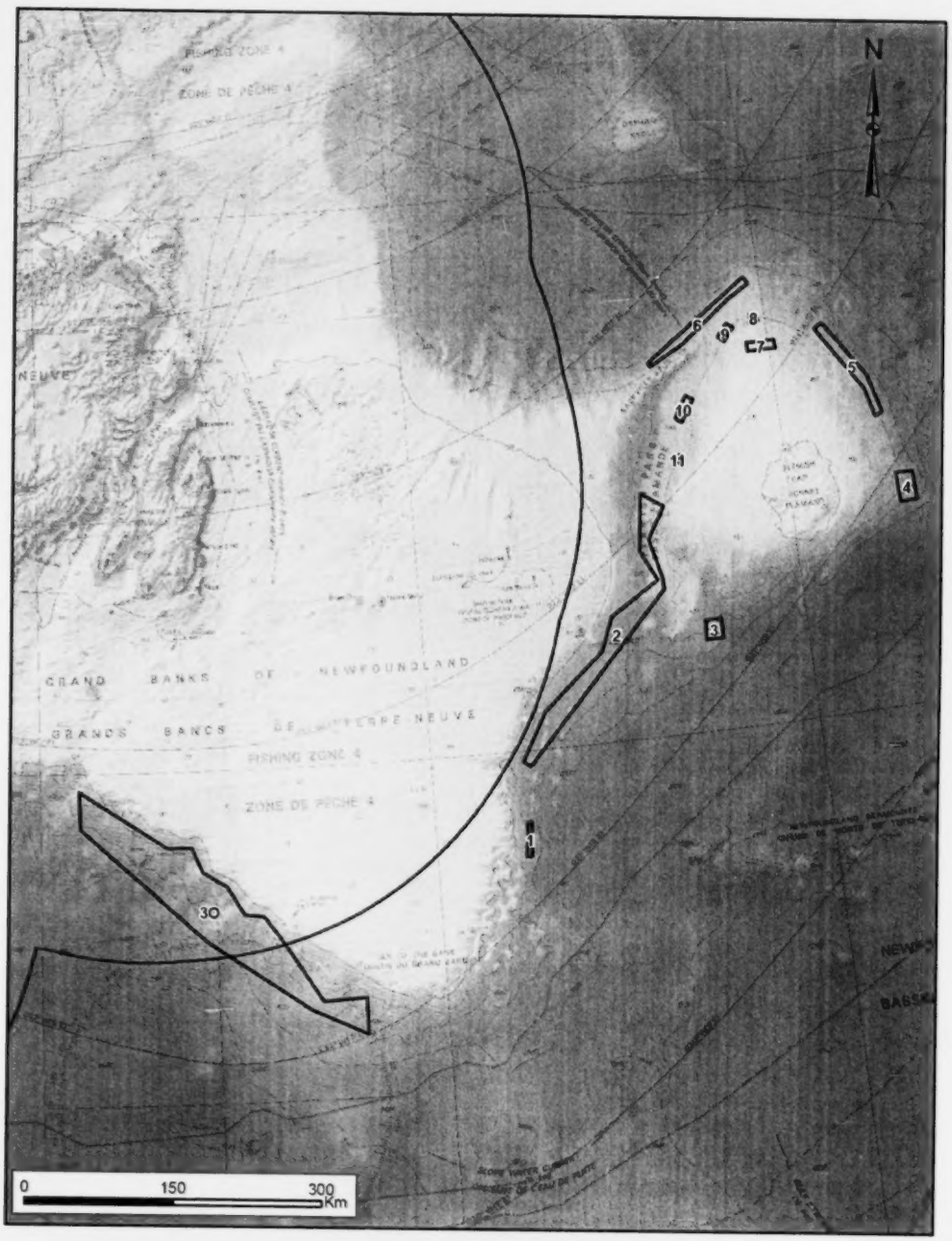

Figure 9. *Location of the spatial closures (blue boxes) implemented by NAFO to protect significant concentrations of coral and sponge in the fishing footprint of the NAFO Regulatory Area (NAFO 2009b). The red line represents Canada's Exclusive Economic Zone.*

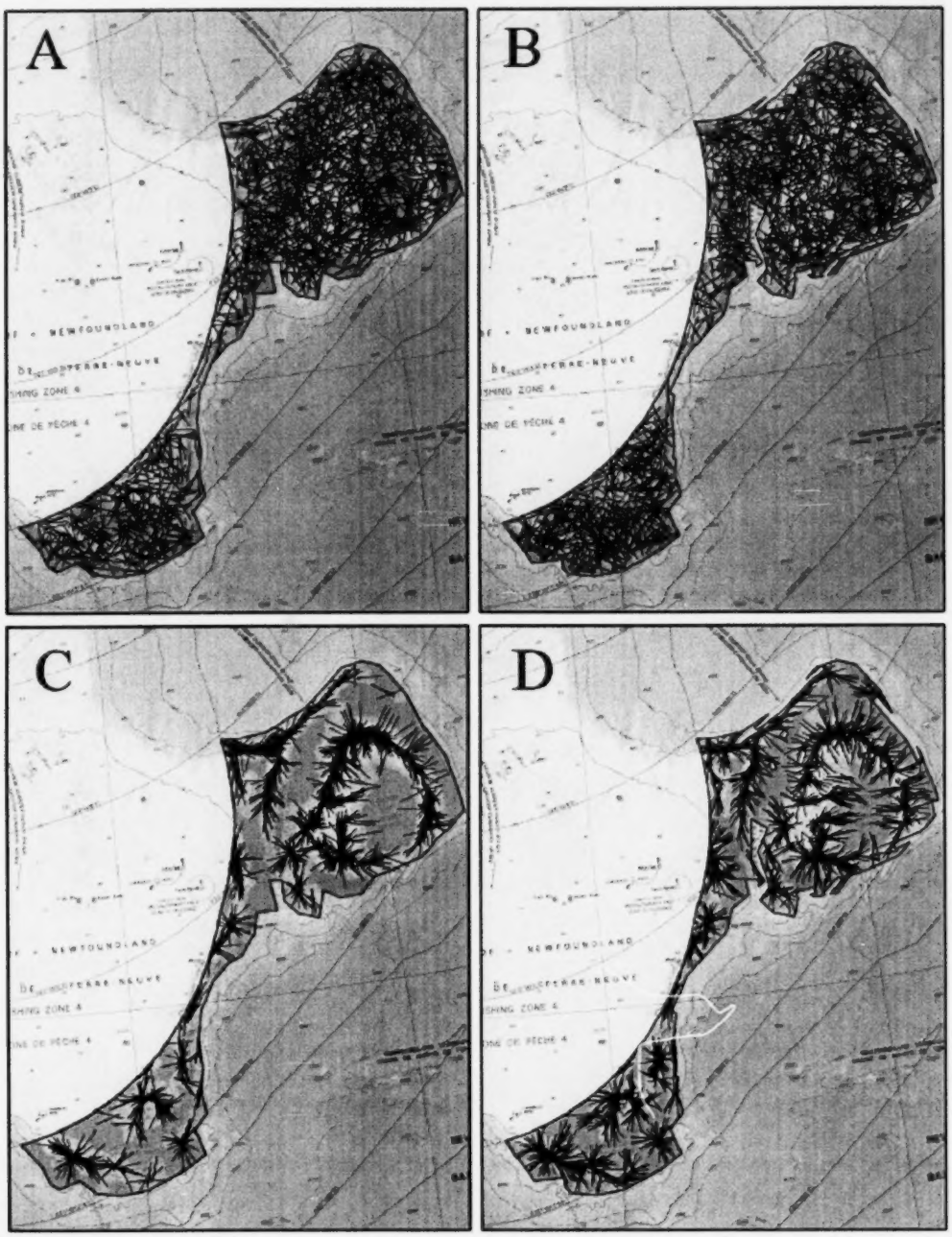

Figure 10. *The placement and orientation of 1500 simulated trawl lines for each of the model Scenarios: A) Scenario 1: Model A random orientation with lines passing through closed areas, B) Scenario 2: Model A random orientation with lines prohibited from entering the closure areas, C) Scenario 3: Model B weighted random orientation with lines passing through closed areas, and D) Scenario 4: Model B weighted random orientation with lines prohibited from entering the closure areas. Simulated trawl lines are placed over top of the fishing effort raster (Figure 2).*

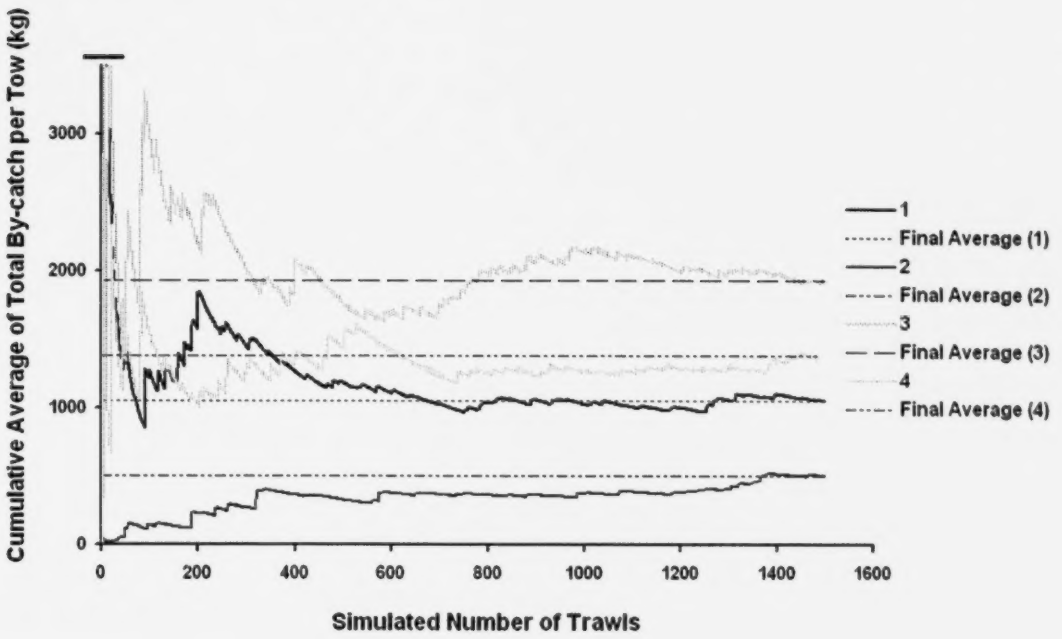

Figure 11. *The cumulative averages (CA) of sponge by-catch from 1500 trawl simulations from each Scenario (1 to 4). The "Final Average" is the last running average calculated and includes total by-catch from all 1500 records. Scenario 1: Model A random orientation with lines passing through closed areas, Scenario 2: Model A random orientation with lines prohibited from entering the closure areas, Scenario 3: Model B weighted random orientation with lines passing through closed areas, and Scenario 4: Model B weighted random orientation with lines prohibited from entering the closure areas. Note that the y-axis is truncated.*

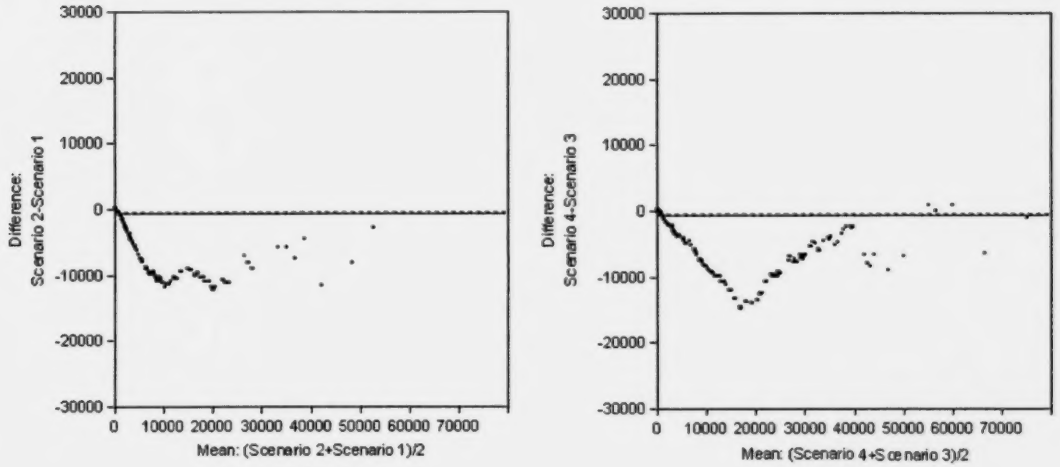

Figure 12. *Graphical display of matched pair differences in sponge by-catch (kg) from 1500 trawl simulations from selected pairs of Scenarios chosen to illustrate the effect of the closed areas within each Model. Scenario 1: Model A random orientation with lines passing through closed areas, Scenario 2: Model A random orientation with lines prohibited from entering the closure areas, Scenario 3: Model B weighted random orientation with lines passing through closed areas, and Scenario 4: Model B weighted random orientation with lines prohibited from entering the closure areas.*

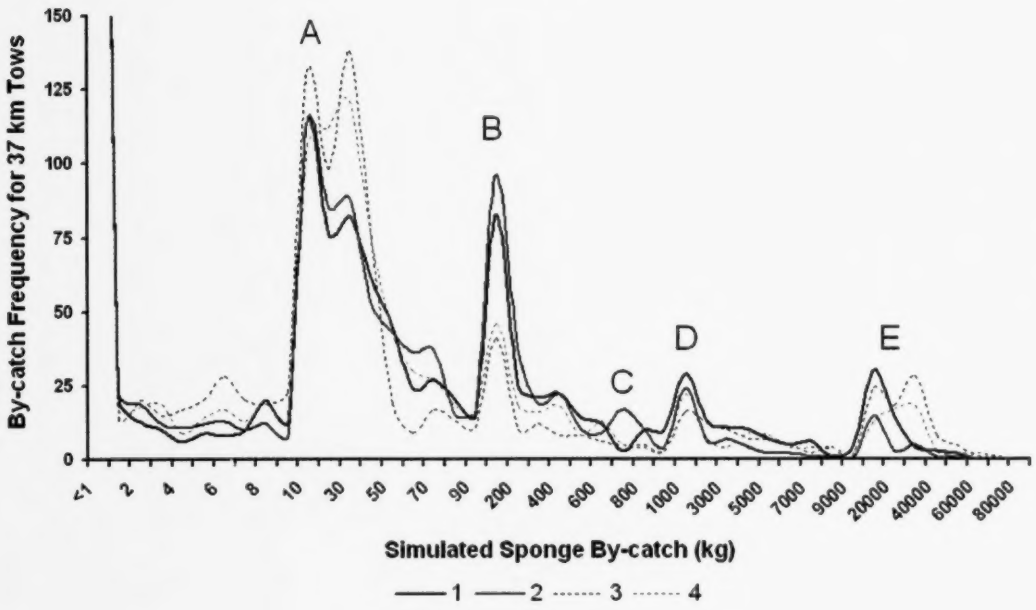

Figure 13. *The sponge by-catch frequency of 1500, 37 km simulated trawl lines from each Scenario (1 to 4): Scenario 1: Model A random orientation with lines passing through closed areas, Scenario 2: Model A random orientation with lines prohibited from entering the closure areas, Scenario 3: Model B weighted random orientation with lines passing through closed areas, and Scenario 4: Model B weighted random orientation with lines prohibited from entering the closure areas. The y-axis for values less than 2 kg is truncated to allow for display of the lower peaks (see text). Letters A to E highlight areas of the curves discussed in the text.*

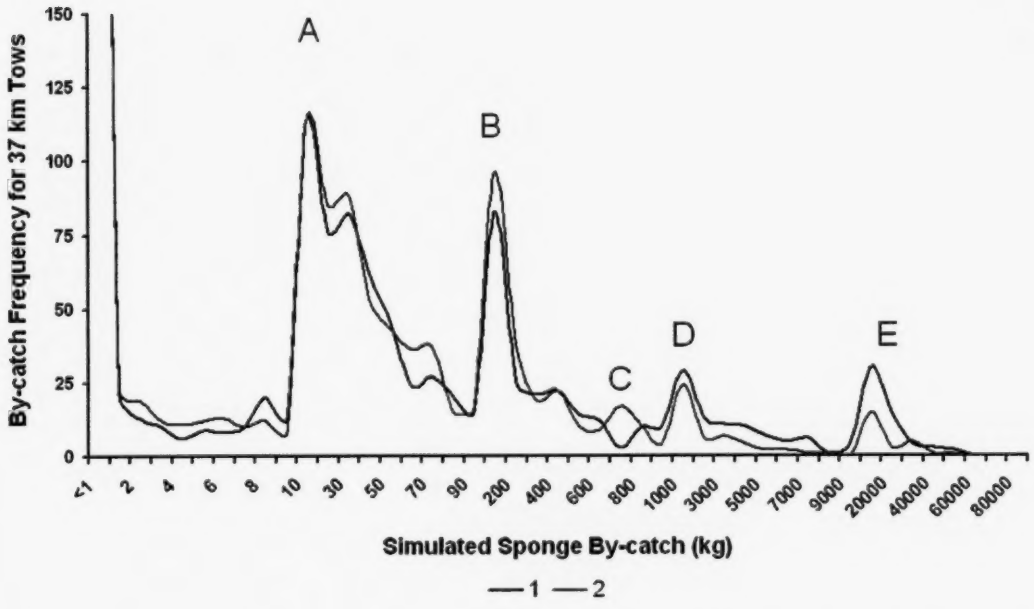

Figure 14. *The sponge by-catch frequency of 1500, 37 km simulated trawl lines for each of the randomly positioned and oriented Scenarios 1 and 2 produced under Model A: Scenario 1: random orientation with lines passing through closed areas; Scenario 2: random orientation with lines prohibited from entering the closure areas. The y-axis for values less than 2 kg is truncated to allow for display of the lower peaks (see text). Letters A to E highlight areas of the curves discussed in the text.*

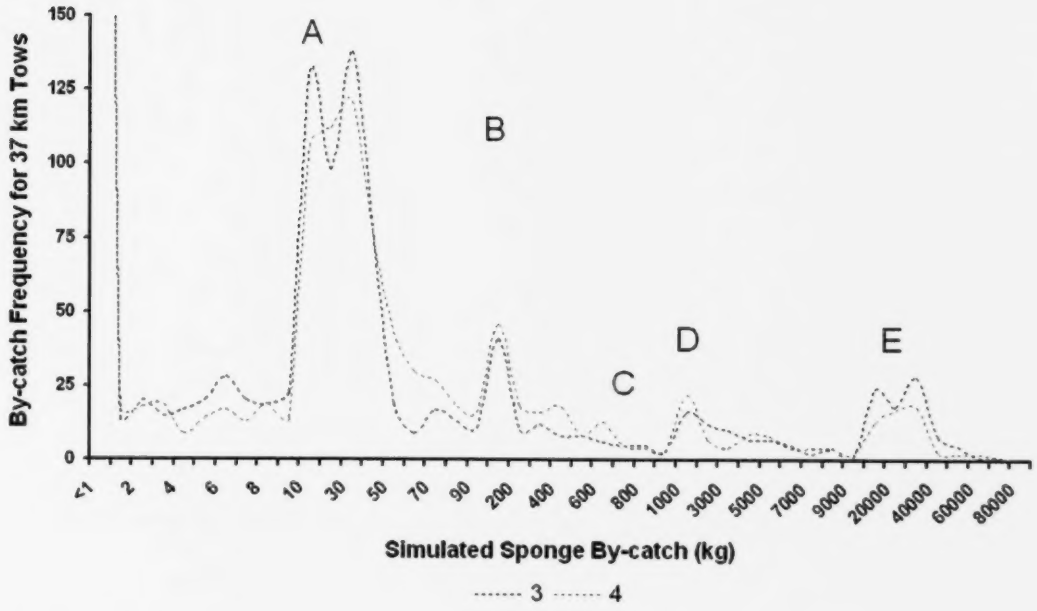

Figure 15. *The sponge by-catch frequency of 1500, 37 km simulated trawl lines for each of the weighted random trawl Scenarios 3 and 4 produced under Model B: Scenario 3: weighted random orientation with lines passing through closed areas; Scenario 4: weighted random orientation with lines prohibited from entering the closure areas. Note that the y-axis for values less than 2 kg is truncated to allow for display of the lower peaks (see text). Letters A to E highlight areas of the curves discussed in the text.*

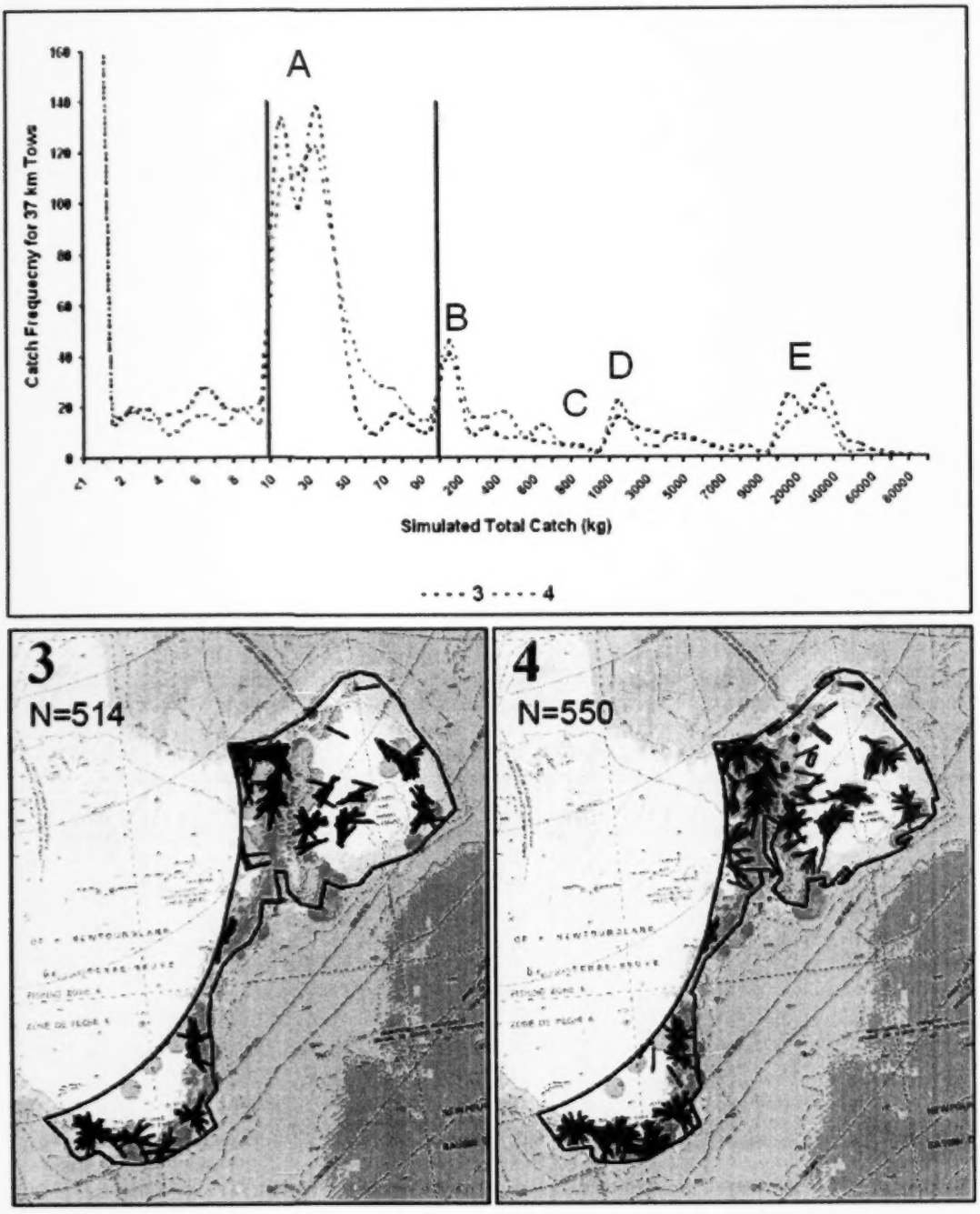

Figure 16. *The location of the simulated trawl lines producing 10 to 100 kg of sponge by-catch (indicated by the blue lines in the top panel) for Scenarios 3 and 4 under Model B: Scenario 3: weighted random orientation with lines passing through closed areas; Scenario 4: weighted random orientation with lines prohibited from entering the closure areas. The IDW sponge biomass raster underlies the position of the trawl lines.*

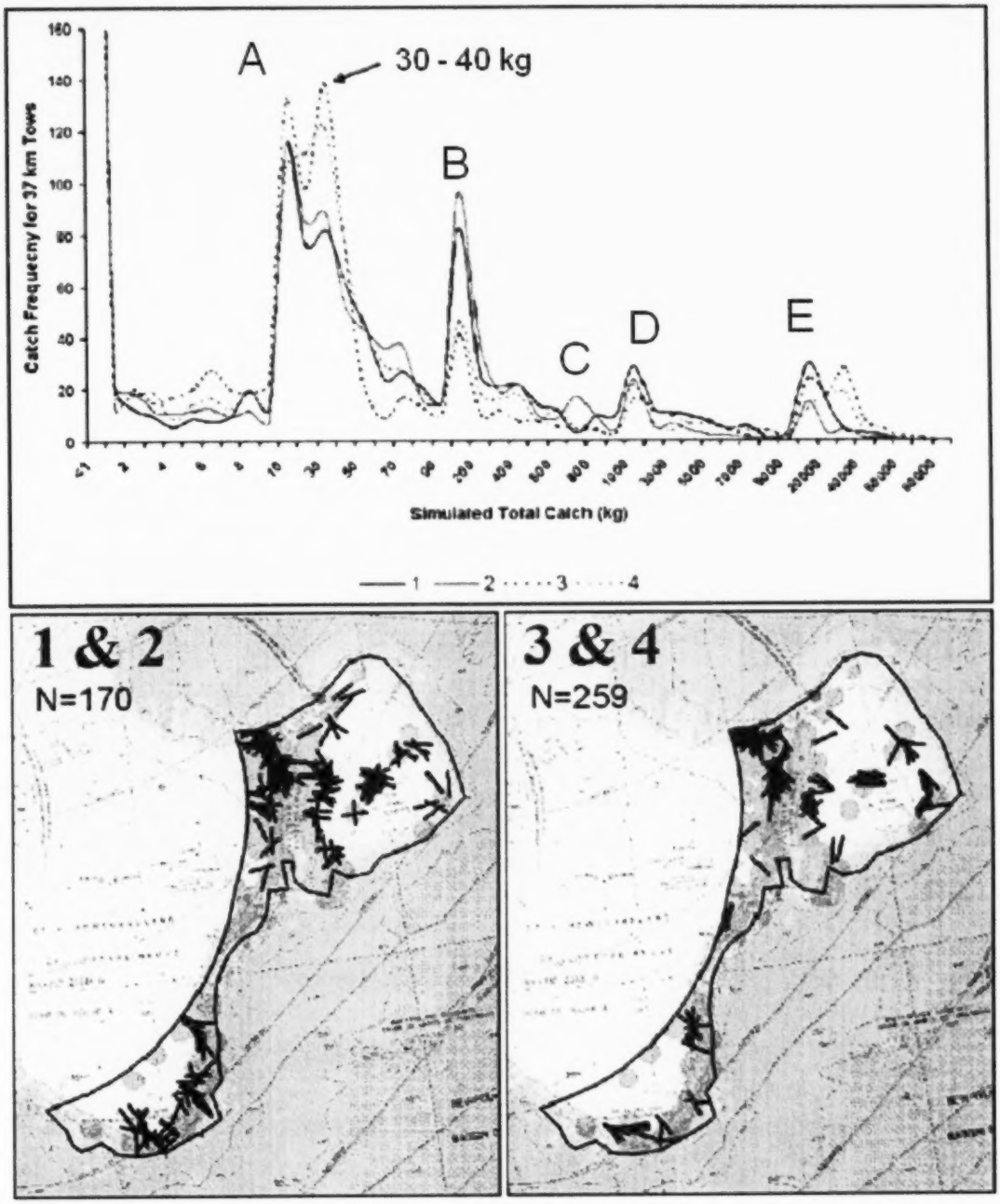

Figure 17. *The location of simulated trawl lines with sponge by-catch of 30 to 40 kg combining data from Scenarios 1 and 2, and 3 and 4 to produce one output for each of Model A and Model B (1: Model A random orientation with lines passing through closed areas, 2: Model A random orientation with lines prohibited from entering the closure areas, 3: Model B weighted random orientation with lines passing through closed areas, and 4: Model B weighted random orientation with lines prohibited from entering the closure areas). The IDW sponge biomass raster underlies the position of the trawl lines.*

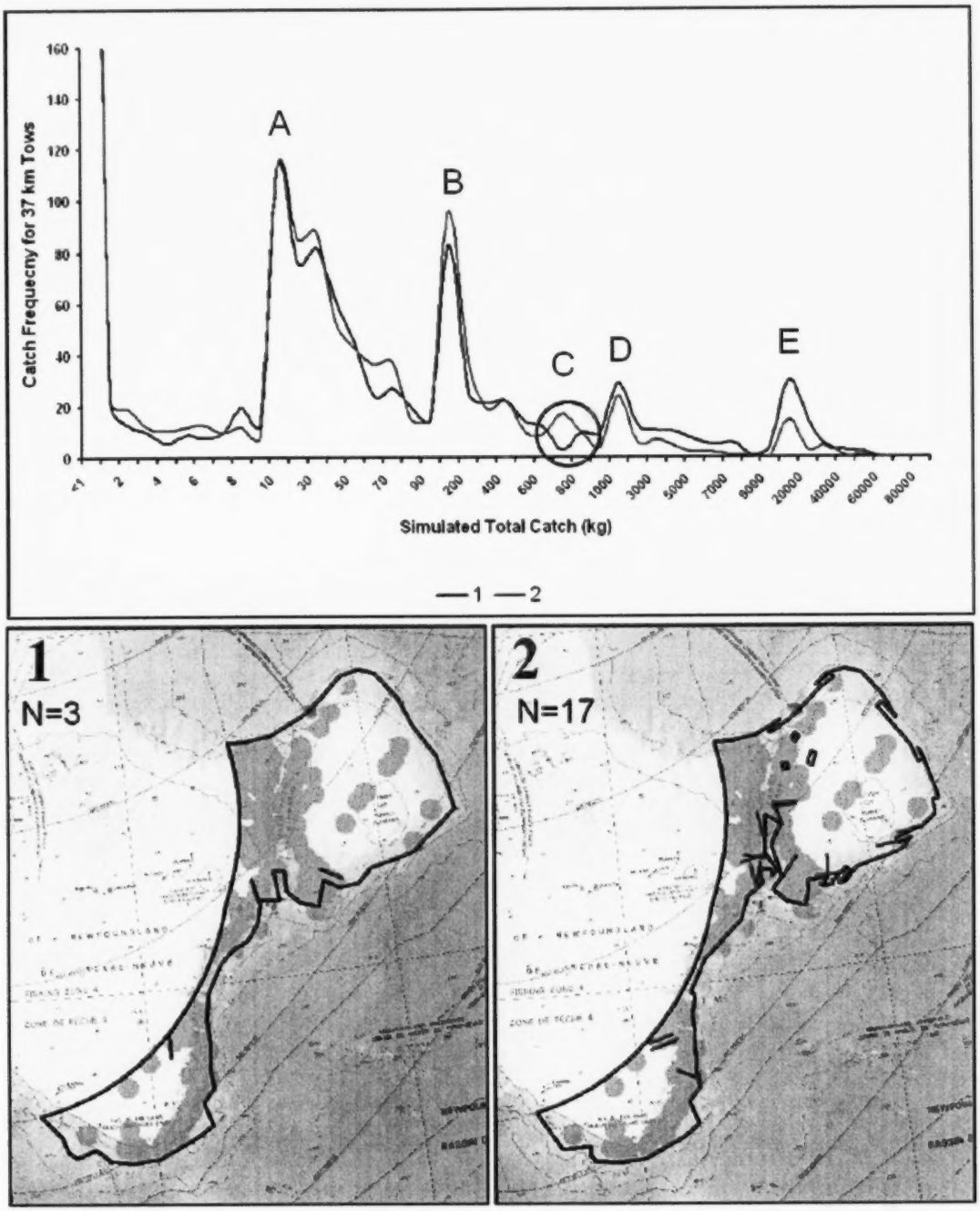

Figure 18. *The location of the simulated trawl lines producing peak C (circled) of sponge by-catch (700 to 800 kg) for Scenarios 1 and 2 under Model A: Scenario 1: random orientation with lines passing through closed areas; Scenario 2: random orientation with lines prohibited from entering the closure areas. The IDW sponge biomass raster underlies the position of the trawl lines.*

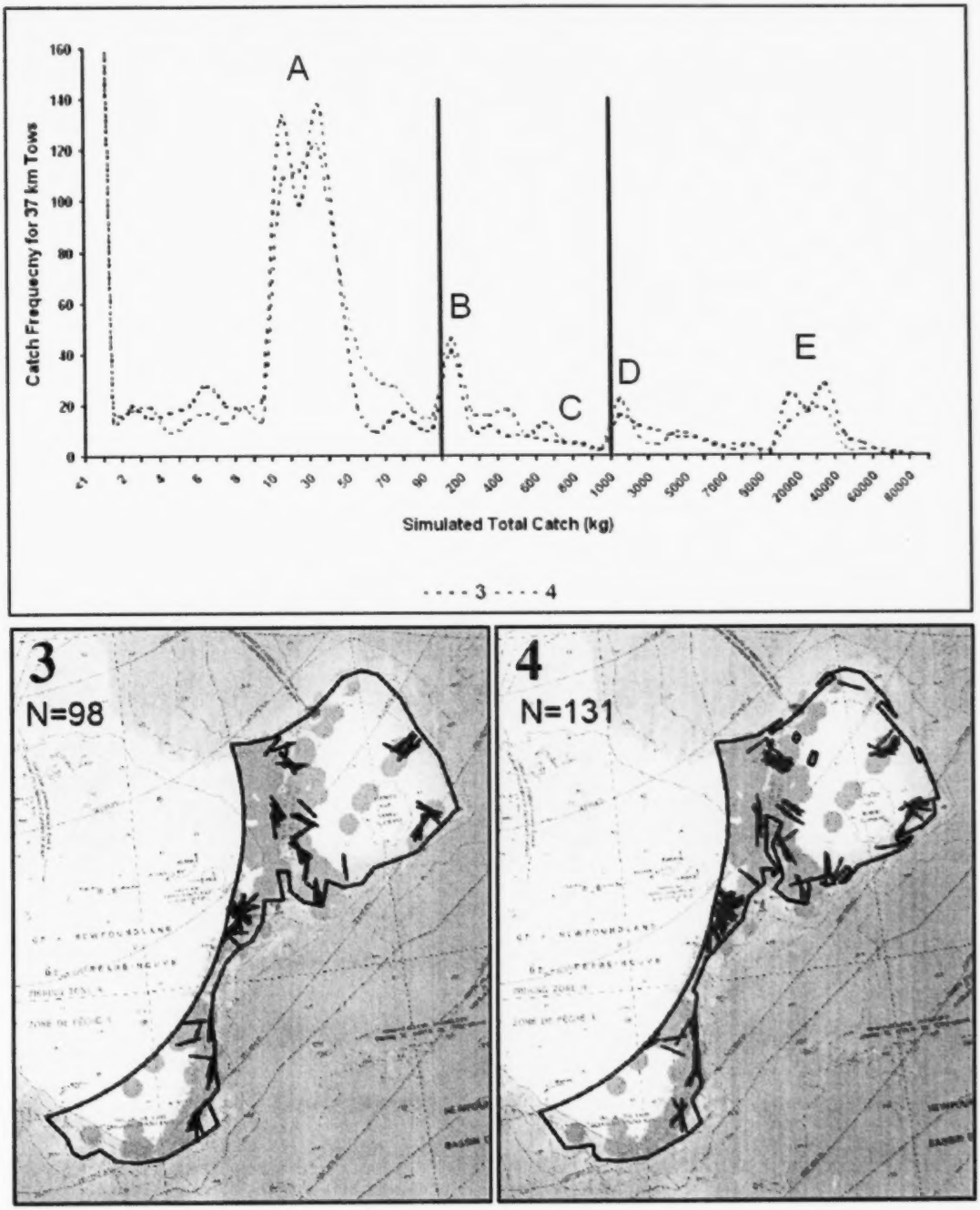

Figure 19. *The location of the simulated trawl lines with catches of 100-1,000 kg (indicated by the blue lines in the top panel) for each of Scenarios 3 and 4 under Model B: Scenario 3: weighted random orientation with lines passing through closed areas; Scenario 4: weighted random orientation with lines prohibited from entering the closure areas. The IDW sponge biomass raster underlies the position of the trawl lines.*

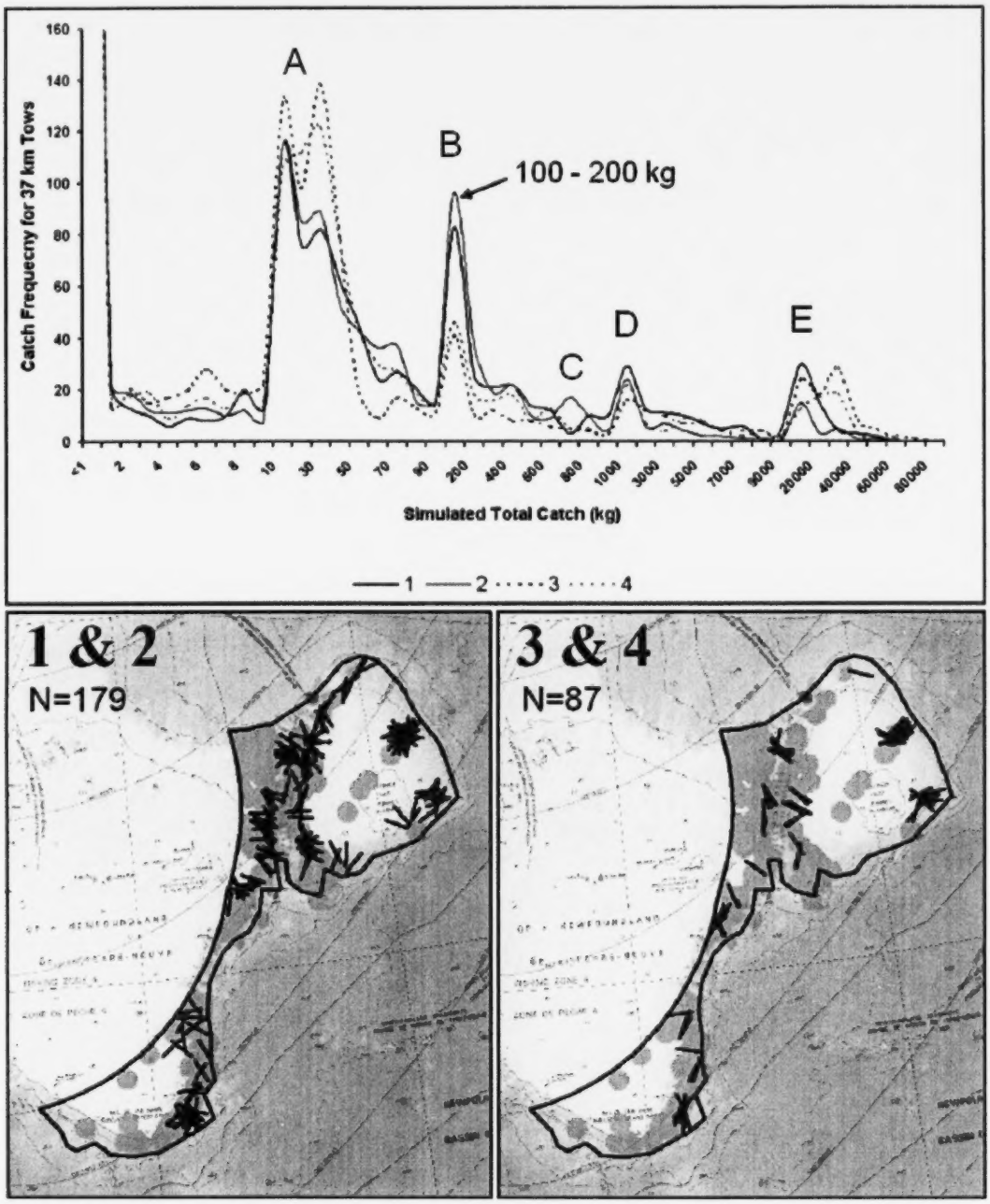

Figure 20. *The location of simulated trawl lines with sponge by-catch of 100 to 200 kg combining data from Scenarios 1 and 2, and 3 and 4 to produce one output for each of Model A and Model B (Scenario 1: Model A random orientation with lines passing through closed areas, Scenario 2: Model A random orientation with lines prohibited from entering the closure areas, Scenario 3: Model B weighted random orientation with lines passing through closed areas, and Scenario 4: Model B weighted random orientation with lines prohibited from entering the closure areas). Note that there are more random trawl lines than weighted random lines in this range. The IDW sponge biomass raster underlies the position of the trawl lines.*

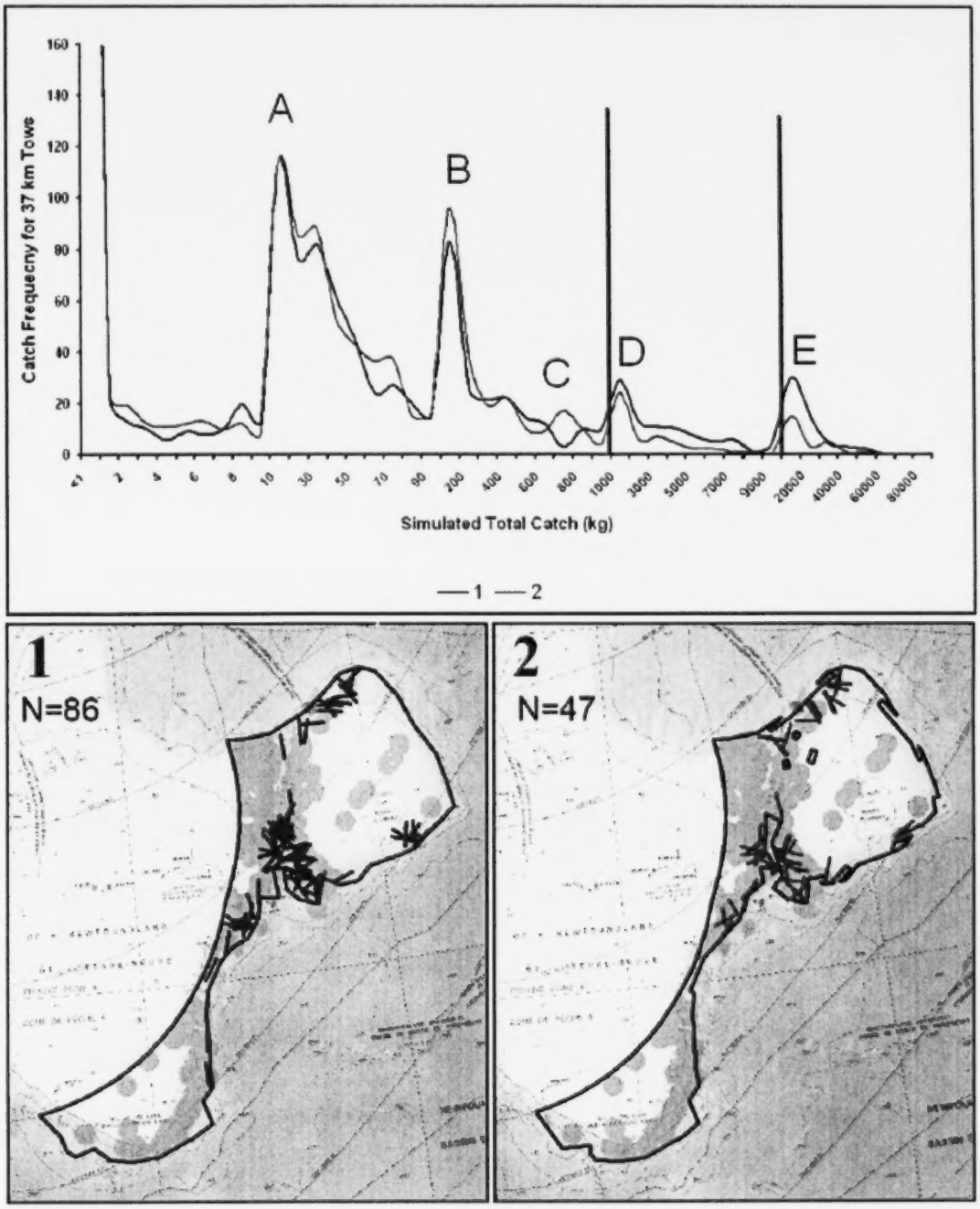

***Figure 21**. The location of the simulated trawl lines producing 1,000 to 10,000 kg of sponge by-catch (indicated by the blue lines in the upper panel) for Scenarios 1 and 2 under Model A: Scenario 1: random orientation with lines passing through closed areas, Scenario 2: random orientation with lines prohibited from entering the closure areas. Note catches in this range are much reduced in Scenario 2 because of the closure area in Flemish Pass. The IDW sponge biomass raster underlies the position of the trawl lines.*

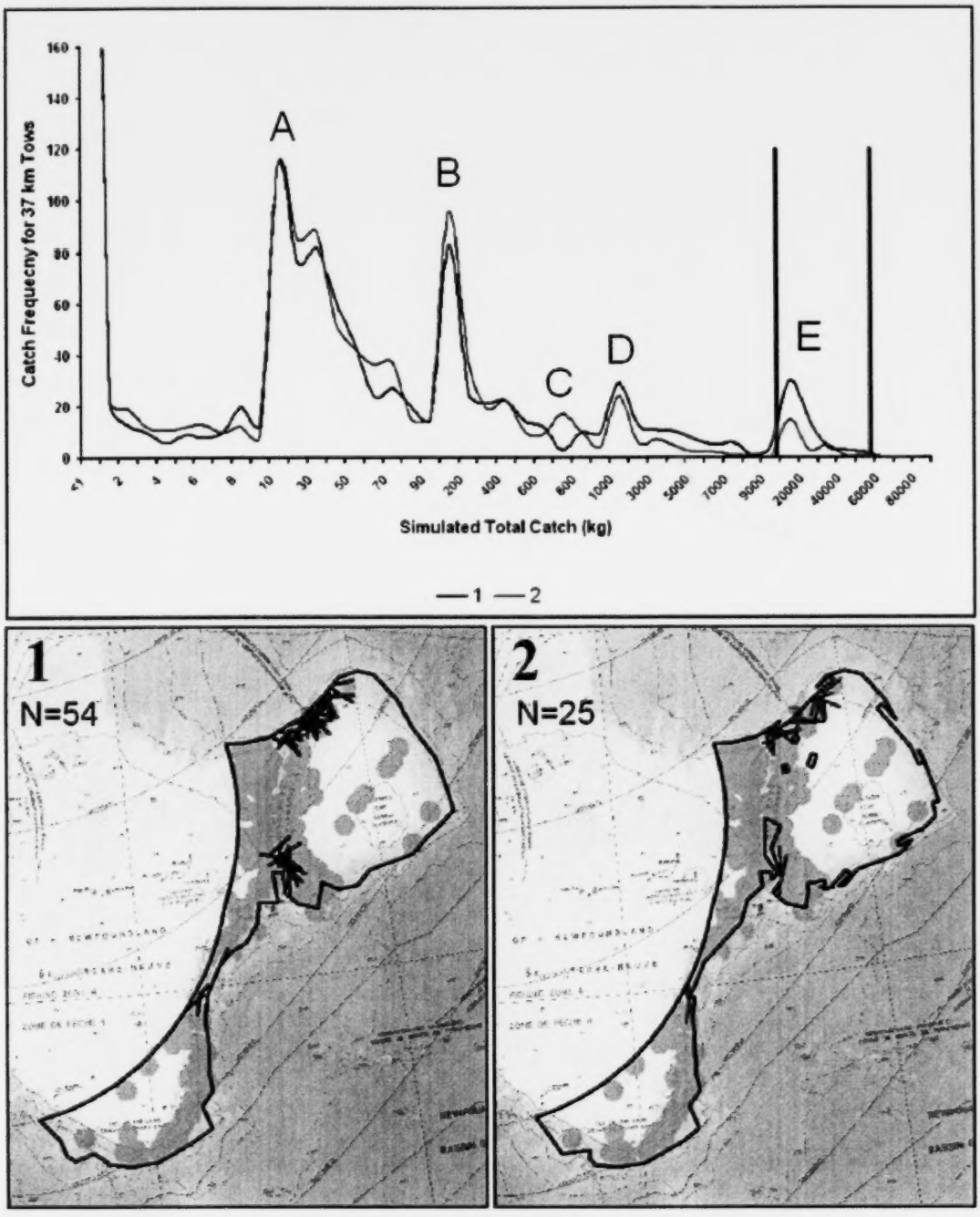

***Figure 22**. The location of the simulated trawl lines producing 10,000 to 60,000 kg of sponge by-catch (peak E indicated by the blue lines in upper panel) for Scenarios 1 and 2 under Model A: Scenario 1: random orientation with lines passing through closed areas, Scenario 2: random orientation with lines prohibited from entering the closure areas. Note catches in this range are much reduced in Scenario 2 because of the closure area in Flemish Pass. The IDW sponge biomass raster underlies the position of the trawl lines.*

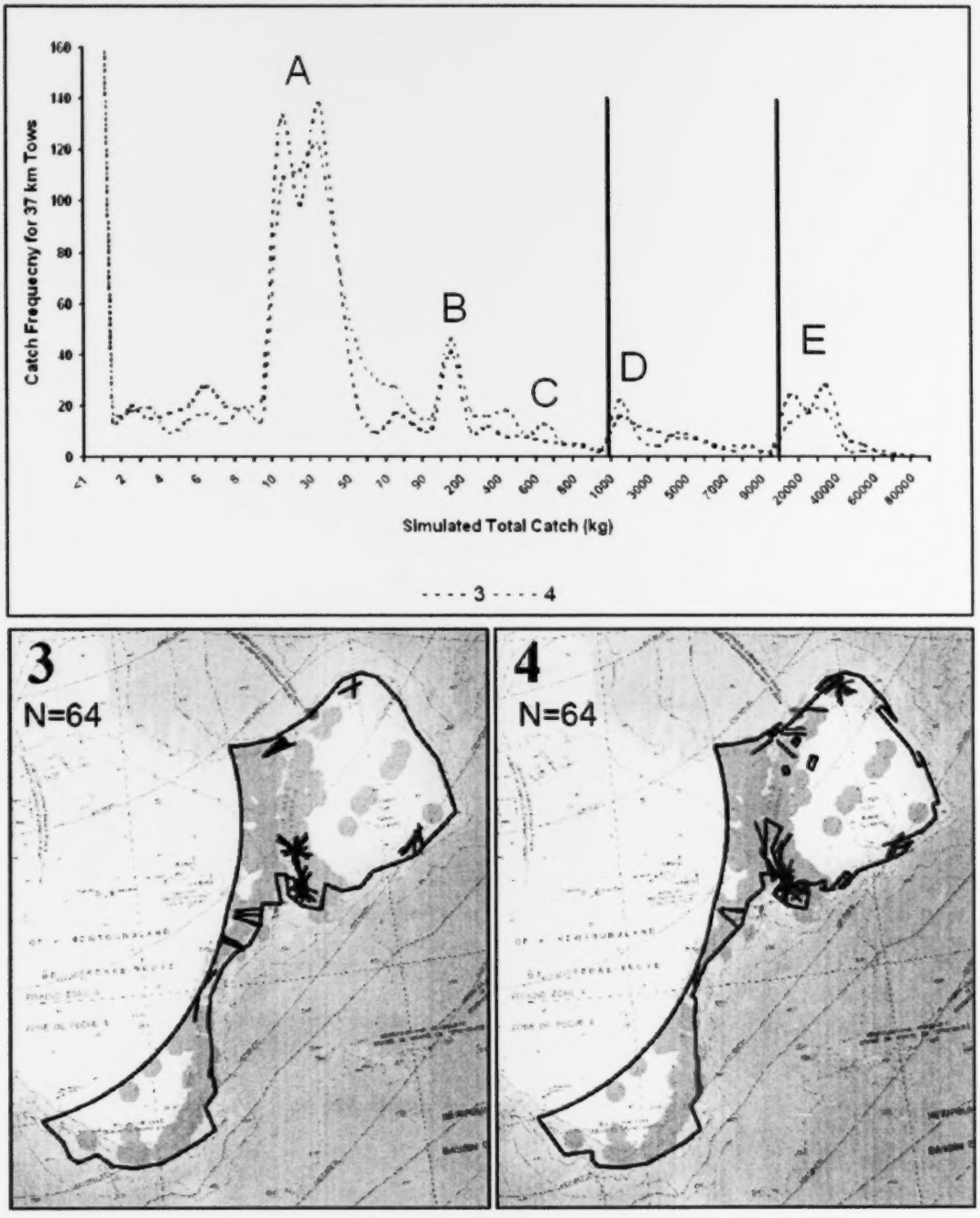

***Figure 23**. The location of the simulated trawl lines producing 1,000 to 10,000 kg of sponge by-catch (peak D indicated by the blue lines in the upper panel) for Scenarios 3 and 4 under Model B: Scenario 3: weighted random orientation with lines passing through closed areas, and Scenario 4: weighted random orientation with lines prohibited from entering the closure areas. The IDW sponge biomass raster underlies the position of the trawl lines.*

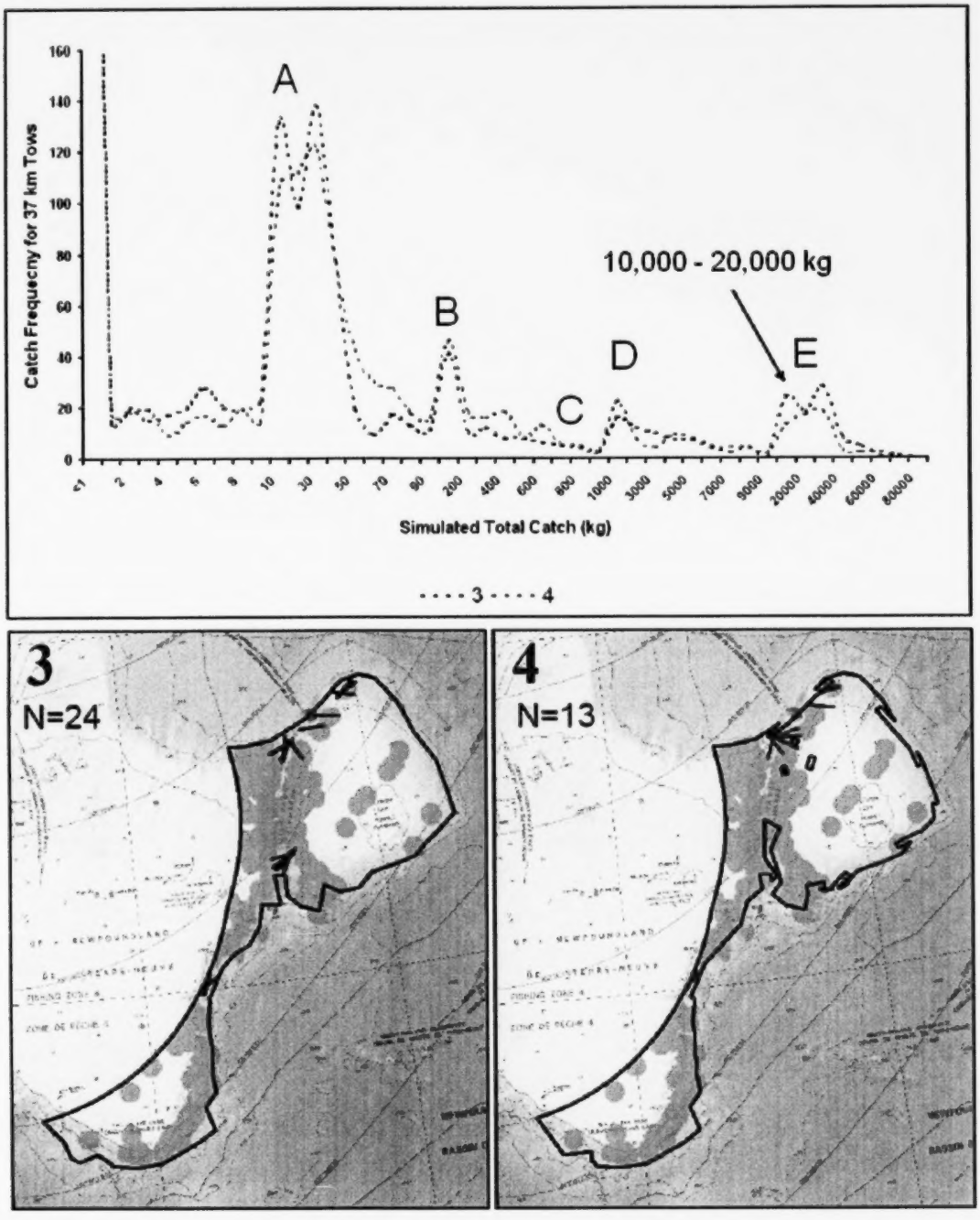

Figure 24. *The location of the simulated trawl lines producing 10,000 to 20,000 kg of sponge by-catch (peak E) for Scenarios 3 and 4 under Model B: Scenario 3: weighted random orientation with lines passing through closed areas, and Scenario 4: weighted random orientation with lines prohibited from entering the closure areas. The IDW sponge biomass raster underlies the position of the trawl lines.*

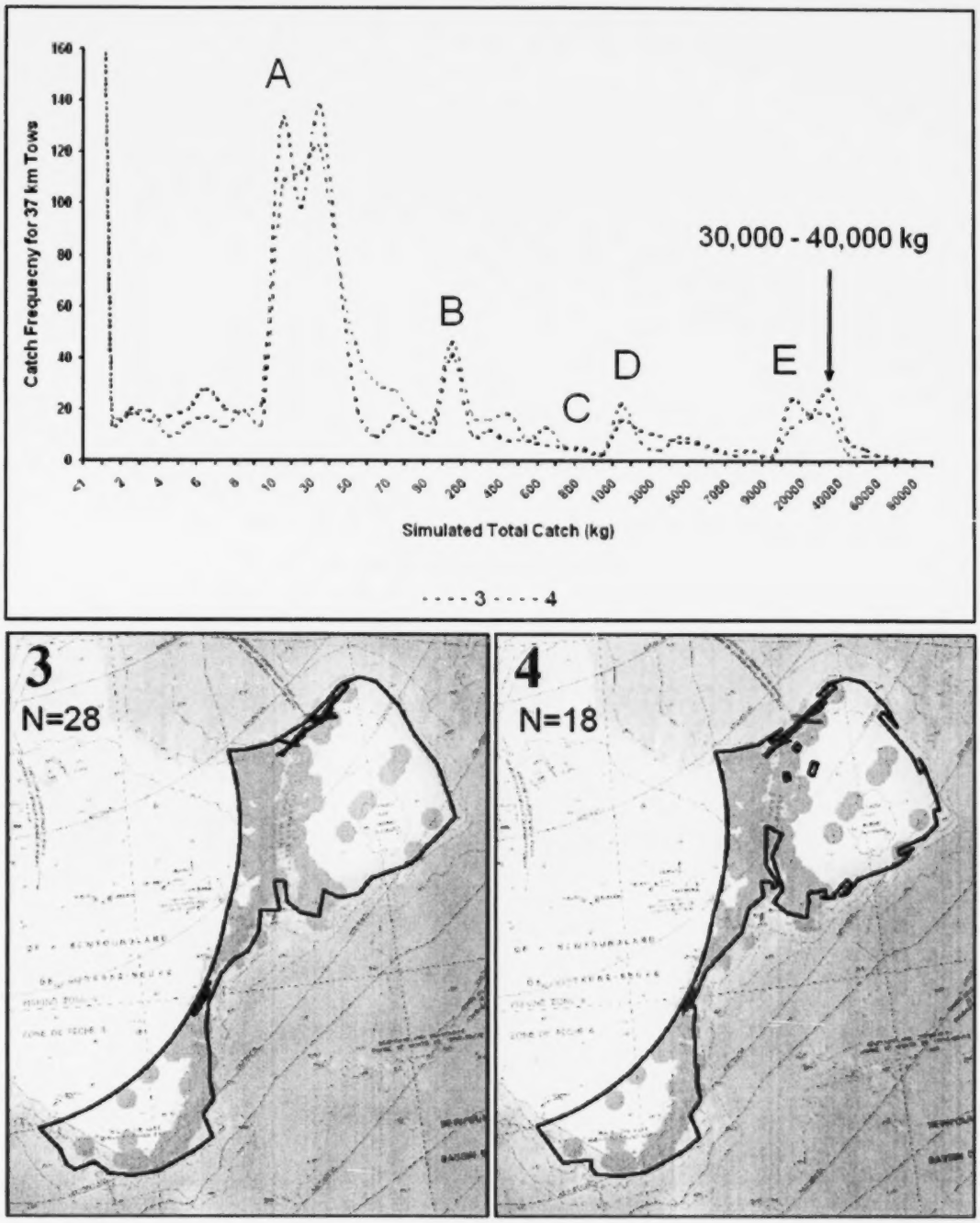

Figure 25. *The location of the simulated trawl lines producing 30,000 to 40,000 kg of sponge by-catch (peak **E**) for Scenarios 3 and 4 under Model B: Scenario 3: weighted random orientation with lines passing through closed areas; Scenario 4: weighted random orientation with lines prohibited from entering the closure areas. The IDW sponge biomass raster underlies the position of the trawl lines.*

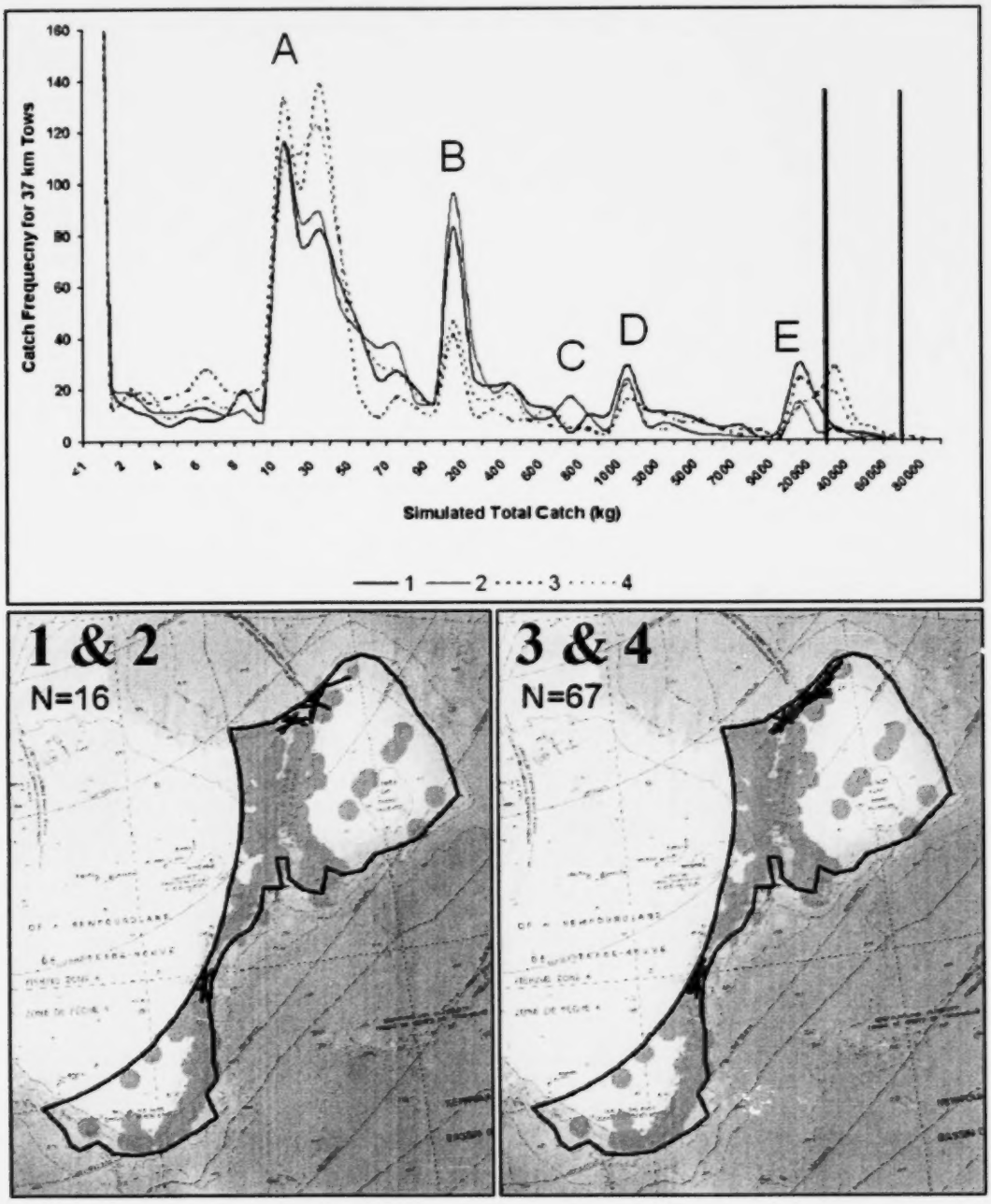

Figure 26. *The location of simulated trawl lines with sponge by-catch of 30,000 to 70,000 kg combining data from Scenarios 1 and 2, and 3 and 4 to produce one output for each of Model A and Model B (Scenario 1: Model A random orientation with lines passing through closed areas, Scenario 2: Model A random orientation with lines prohibited from entering the closure areas, Scenario 3: Model B weighted random orientation with lines passing through closed areas, and Scenario 4: Model B weighted random orientation with lines prohibited from entering the closure areas). Note that there are more weighted random trawl lines than random lines in this range. The IDW sponge biomass raster underlies the position of the trawl lines.*

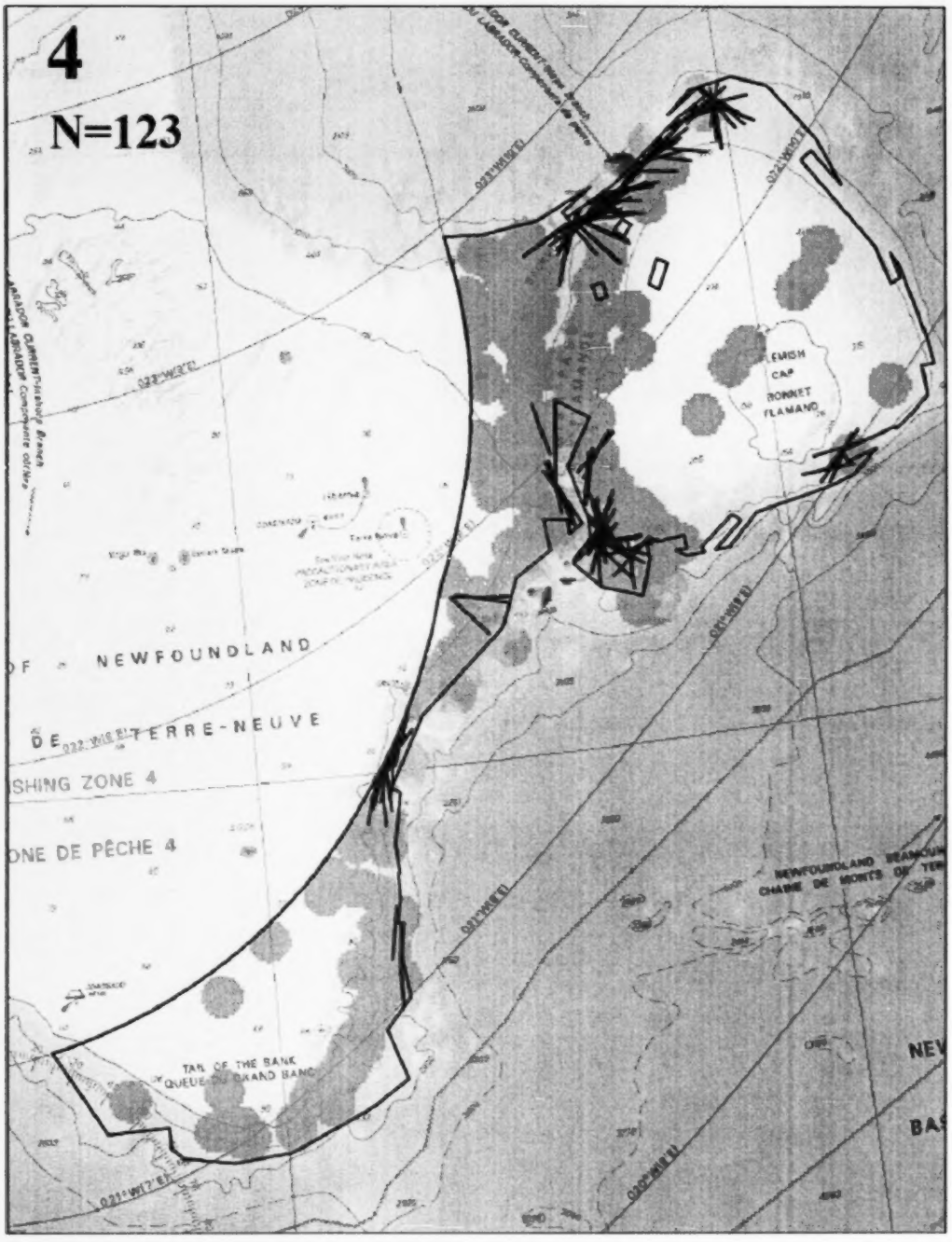

Figure 27. *The location of the simulated trawl lines producing ≥ 800 kg of sponge by-catch for Scenario 4 under Model B: weighted random orientation with lines prohibited from entering the closure areas. This scenario most closely approximates real-world fishing practices. The IDW sponge biomass raster underlies the position of the trawl lines.*

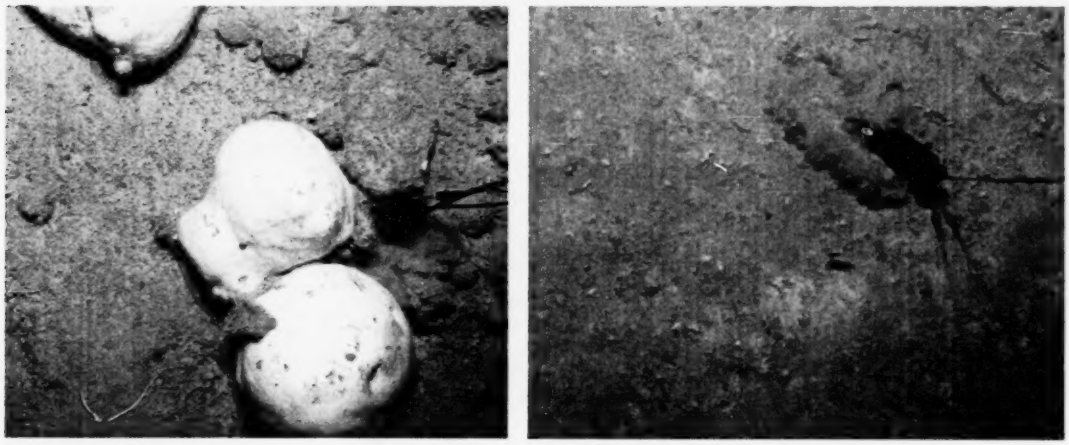

Figure 28. *Large Geodia spp. sponges found in 1400 m in the closed area on Sackville Spur (A) and typical bottom observed in the adjacent fished areas at about 1200 m depth. The black weight in the images is approximately 10 cm in length.*